URBAN WATER USE: MOVING TOWARDS THE INTEGRATION OF LAND USE AND WATER SUPPLY PLANNING

by

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STATEMENT OF DISSERTATION APPROVAL

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ABSTRACT

Clean and reliable water supplies are essential to support growing populations and economic activity, yet population growth and changing climatic conditions are stressing water supplies. There are two strategies to plan for urban water supplies: the first is to secure and develop clean and reliable sources, and the second is to manage water demand. The second option seeks to reduce water consumption so that additional supplies are not needed. Traditional approaches to managing demand include education, water use restrictions, and improved efficiency. A novel approach is designing cities and neighborhoods to promote conservation. This dissertation will explore how urban planners can shape the built environment in order to promote urban water conservation.

I begin with an exploratory analysis of how the built environment affects water use. I gathered measures of the built environment, demographics, and climate to explore the drivers of water use, utilizing a detailed dataset of 77,256 properties and water use in Salt Lake City, Utah. The measures of the built environment were some of the strongest predictors of urban water use in Salt Lake City. I also explored how the built environment at the neighborhood level influenced the water use of the buildings within the neighborhood. This investigation indicated that water use was a characteristic of a neighborhood, as well as being influenced by the physical characteristics of a single property. The empirical evidence presented in this dissertation, along with corroborating evidence from other research, indicates that the built environment influences how cities use water. In order to identify how urban planners can promote water conservation, I conducted interviews with water managers, urban planners, and water resource researchers from five western states that had experience, or no experience, integrating land use planning and water supply planning. The interviews revealed opportunities and challenges for urban planning to contribute to existing water conservation efforts. I conclude the dissertation with specific planning strategies to promote urban water conservation.

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CHAPTER 1

PLANNING FOR URBAN WATER CONSERVATION

Clean freshwater is critical to support human populations and economic development. All civilizations on earth built their foundations on the availability of freshwater. Rome was built on the Tiber, Moscow on the Moskova, London on the Thames, and so on (Figure 1). When cities' access to water became limited, human ingenuity brought the water through canals and aqueducts. On the other hand, civilizations have collapsed when freshwater supplies were depleted. For example, the Aztecs could not withstand the siege of Spanish Conquistadores because water supplies to their island city were cut (Levy, 2009). The Khmer empire of Southeast Asia likely fell due to failed efforts to battle drought (Choi, 2012). The Ancestral Puebloans of the U.S. desert southwest had to permanently relocate out of their traditional homeland due to widespread and long-term drought (Diamond, 2005). Obviously civilizations in the desert have had a much harder time with water, and "only one desert civilization, out of dozens that grew up in antiquity, has survived uninterrupted into modern times," Egypt (Reisner, 1986, p. 3). The availability of freshwater to support human populations as a requisite is beyond dispute. In our modern civilization, water sustainability will be a defining challenge of the future, because the global population of seven billion, and rising, still requires abundant clean water.

Drivers of water stress in cities

The principle drivers that stress water supplies are climate change, population growth, and land use change (Schnoor, 2010). In the Western U.S., climate change is shifting the timing of precipitation from winter snow to rainfall, significantly reducing water supply in the late summer months (Bardsley et al., 2013; Barnett et al., 2008; Hale et al., 2015). Instead of snow gradually melting in the mountains throughout the summer, most of the precipitation comes as rain and the snow melts quickly and early, leaving water supplies stressed when demand is high at the end of the growing season. Droughts further reduce water supplies, and the probability of prolonged regional droughts in the Western U.S. as a result of climate change is likely (Cook et al., 2010). Adding to the stress caused by climate change, every arid and semi-arid Western state is increasing in population (Figure 2). Growing populations and urbanization in the West are increasing the demand and competition for scarce water supplies (Bardsley et al., 2013; Gober, 2010; Hale et al., 2015). As urban populations increase and agricultural lands are converted to urban uses, will water be used for agriculture or for watering lawns? These challenges are likely to continue and a range of projected climate and growth scenarios predict gaps between supply and demand across the western region (U.S. Bureau of Reclamation, 2015). The future of water availability is uncertain, and is substantially influenced by global and regional changes.

The vulnerability of water stressed cities

Many cities in arid regions are vulnerable to reductions in existing water supplies. Unlike the historical examples of cities locating near rivers, today the Western U.S. has several major metropolitan areas with limited local freshwater resources, i.e. Los Angeles, Phoenix, and Las Vegas. These "beachheads" of civilization in the desert could not exist without dams and hundreds of miles of pipes and canals (Reisner, 1986). The current populations exist because as "one builds infrastructure and makes water available, it ensures the growth in the population for which you have planned" (Schnoor, 2010, p. 2).

Further supply augmentation and dam building may not be feasible in the future due to lack of good places to build dams, already utilized water sources, and the high environmental and economic costs of new dams (Figure 3).

Figure 4 provides cost estimates for supply augmentation projects compared to water demand management actions (NRDC, 2014). Managing demand is then critical to ensure that existing water supplies can support current and future populations. In urban areas, managing demand to reduce water consumption can be just as effective as increasing supplies. For example, overall water withdrawals across the United States have not increased substantially in recent decades despite increasing populations, likely due to improved efficiency and water conservation efforts (Schnoor, 2010). The end goal of managing demand is to reduce water use, so that additional supplies are not needed. Demand management and reducing water use can also make a city more resilient to the uncertainties of the future. There are two principle mechanisms to reduce use, improve the efficiency of how water is used and change the behavior of water users (Figure 5).

In order to improve how we use water, we must better understand how water is used in cities. The way in which we build cities directly affects water use and supply. For example, building characteristics such as the size of the lot, the amount of turf, and the type of building all affect water use (Guhathakurta & Gober, 2007; Polebitski & Palmer, 2010; Rockaway et al., 2011). We also know that neighborhood characteristics such as demographics, density, and diversity influence how much water is consumed (Chang et al., 2010; Guhathakurta & Gober, 2007; House-Peters et al., 2010; Rothfeder et al., *in review*). At the city scale, the cumulative impacts of the lower scales contribute to total water use. For example, municipal water use in Europe is about 50% of that in the U.S. due to the fact that the lots on which houses are built are much smaller and more people live in apartments compared to U.S. (Novotny, 2010). Since there is a link between how we build cities and urban water use, urban planning clearly has a role to play in how cities use water.

Planners and water conservation

Traditionally, urban planners have not been involved in the water management of cities. Rather, it was the role and duty of engineers to supply cities with water. Engineers have been involved with water supply from the earliest settlement of the Western U.S. (Gober et al., 2013). The primary motivation for water provision was to make water available for agriculture and ensure that people could live in an arid landscape. Small dams and irrigation ditches created by the earliest European settlers could support only small populations. But with the passage of the 1902 Reclamation Act, engineers employed by the U.S. Army Corps of Engineers began building larger dams and water infrastructure that allowed the growth of most of the major cities in the west. For example, the Salt River project in Arizona supports Phoenix, the Colorado River Aqueduct supports Los Angeles, and so on. When populations were smaller, engineers successfully designed solutions to water shortages. However, as urban populations in these cities continue to grow, engineers would benefit from the participation of land use planners to help cities make do with existing supplies.

Planners influence how water is used in cities by shaping the built environment through land use regulation: including zoning, ordinances, and building codes. Furthermore, planners are skilled collaborators who can help communities consider what the future may and should be (Klosterman, 2013). Clean freshwater is crucial to the creation of good places, and it is urban planners who have the duty to create "good places for people—not only physically, but also socially, economically, and environmentally" (Godschalk, 2014). However, urban planning has generally not involved itself in water supply planning or conservation, despite the potential to aid water conservation efforts. This dissertation is an effort to link urban planning and water management.

Outline of dissertation

My dissertation is structured in five chapters. After this introduction, the second chapter of the dissertation is a review of the literature on urban water use. I focus on the ways in which the built environment affects water use as well as reviewing other key variables that influence urban water use. I synthesize key themes among studies such as the scale of analysis and data availability. I conclude the literature review with the existing limitations of urban water use research, specifically the lack of detailed data, the fact that urban land use types such as commercial are often ignored, and the common reliance on aggregated studies. My research in the next chapters addresses these shortcomings, improving and building upon previous research.

The third chapter is an investigation into the drivers of urban water use in Salt Lake City, Utah. I developed empirical models of urban water use in order to reveal the predictors of water use. This research improves upon past efforts by utilizing a large and detailed disaggregated dataset of water consumption. The models developed in this research are based on the water use records of 77,256 buildings in Salt Lake City, Utah. The annual water use patterns revealed the importance of seasonality and that most of the water is used for outdoor irrigation in the summer months. The models themselves demonstrated the relative contribution of climatic, built environment, and demographic variables. The built environment variables, which included measures of the physical properties, improved the explanatory power substantially for all models. Based on these findings, I recommend that city and water managers investigate design regulations on properties to promote water conservation.

In order to further understand how water is used in cities, the next chapter investigates patterns of water use at the neighborhood level. Previous research has shown that spatial clusters of water use exist in cities, where there are areas of high and low use. Employing the detailed database developed in the previous chapter, as well as a regional database on characteristics of neighborhoods, I used multilevel modelling to investigate the effects of neighborhoods on water use at the parcel scale. This research is unique as it is the first to test if there are neighborhood effects on urban water use. The results indicate that there is a strong neighborhood effect, where certain neighborhood characteristics influence the water use of parcels within them. These results suggest planning and design strategies at the neighborhood level that planners can use to promote urban water conservation.

Based on the results of the previous two chapters that demonstrate the built environment's effects on water use, there is strong empirical evidence that city planners have an important potential role to play in urban water conservation. While supply augmentation may no longer be an option, managing urban demand and promoting urban water conservation will be critical to sustain water resources. Furthermore, there are problems when land use planning is not coordinated with demand management, as new developments permitted without regard to water supplies further strains water supplies. Urban planners can expand the suite of tools that are available to water managers, and can partner in efforts to promote water conservation. I conducted interviews with water managers, urban planners, and water resource experts from five western states to gain insights into how land use planning and water supply planning can be integrated. The interviews revealed key themes to consider when integrating land use planning and water supply planning, as well as specific strategies for urban planners to implement. Finally, I conclude this dissertation with specific recommendations for city planners to promote water conservation. I also suggest avenues of future research to help address unanswered questions.

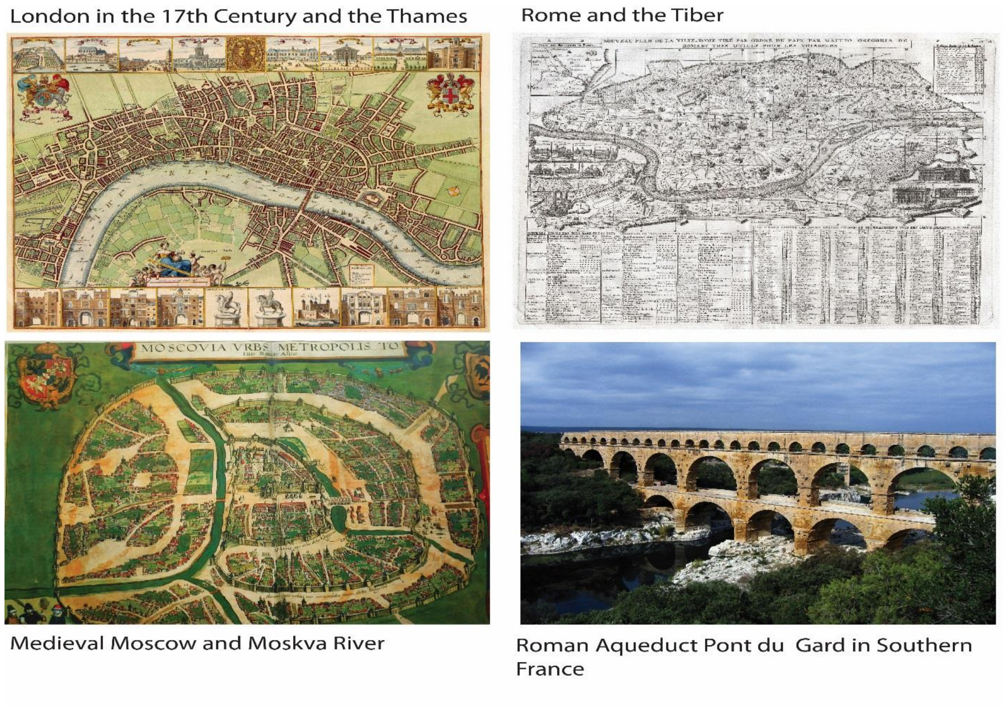

Figure 1 Examples of ancient cities locating next to rivers, as well as using aqueducts to bring water to cities.

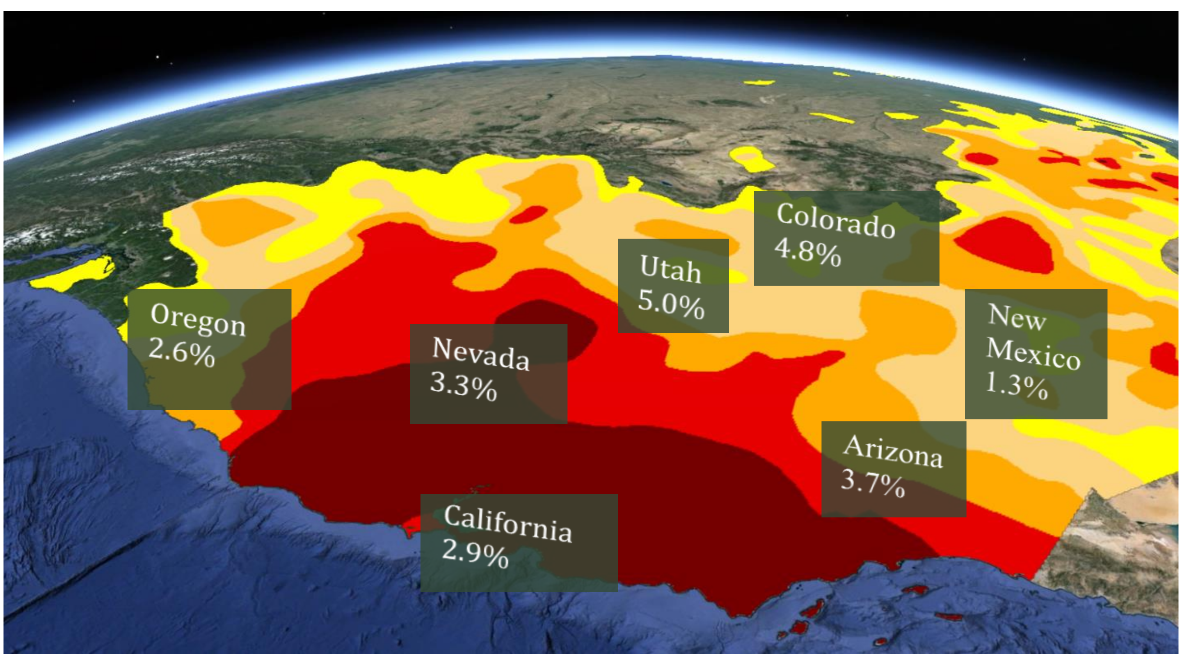

Figure 2 Percent change in population 2010-2013 (U.S. Census Bureau 2014) and drought conditions where darker red indicates more severe drought (U.S. Drought Monitor January 2014).

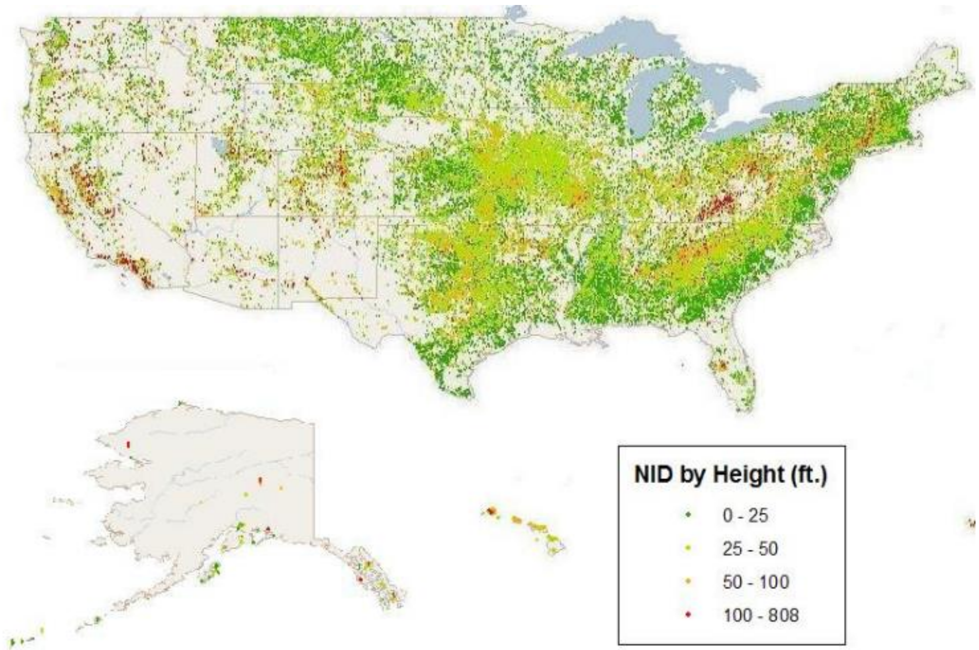

Figure 3 Location of dams (n=74,096) across the U.S (from U.S. Army Corps of Engineers, 2014).

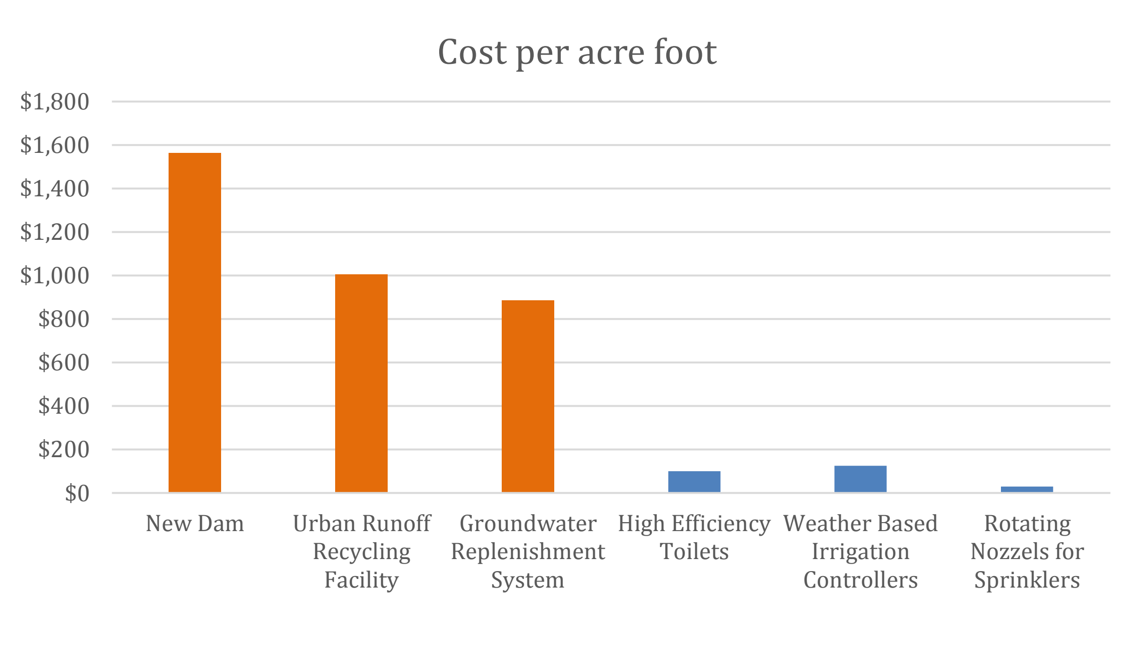

Figure 4 Cost comparison for supply augmentation (orange) and conservation actions (blue)

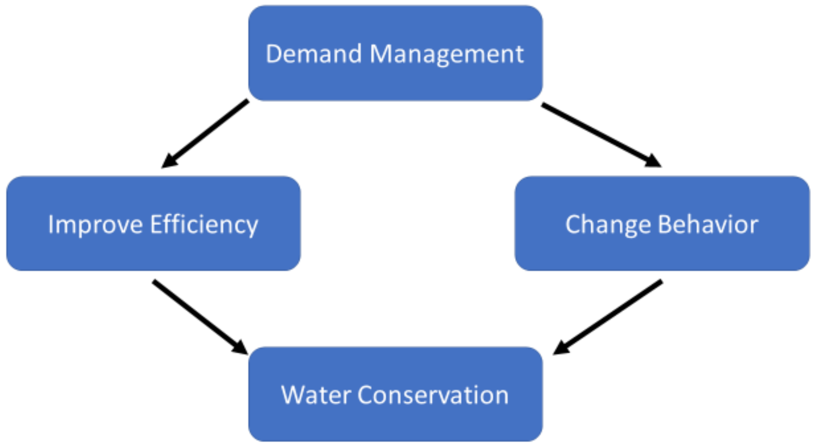

Figure 5 Demand management and water conservation

CHAPTER 2

LITERATURE REVIEW

In this literature review, I synthesize previous research that has been conducted on urban water use to highlight the effects of the built environment on water use. I also include a review of other key variables such as demographics, price, and climatic conditions. In addition, I review the methodologies that have been employed to examine and model urban water use. The research in this dissertation seeks to build upon previous research, so I review the shortcomings of the previous literature as well. I conducted a literature review on Google Scholar; JSTOR; and through the University of Utah Marriot Library, using keywords such as: water demand, water use, urban water use, water demand modelling. Following this initial search, I worked with several colleagues to build an online database of journal articles and reports related to water use. This database, along with recently published literature reviews on urban water use (Donkor et al., 2012; House-Peters & Chang, 2011) were the foundation of my literature review.

The way in which water is used in cities is a timely topic. House-Peters and Chang (2011) illustrate the extent to which academic researchers are attracted to this topic (Figure 6). Despite the increase in published academic literature on water use, further research is warranted. Previous research has been constrained by lack of parcel-level characteristics (Arbués et al., 2004), urban land use data (Kenney et al., 2008), and fine grained water use data (Gaudin, 2006). Advances in data sources such as remotely sensed data and the availability of parcel-scale water improves the analysis water use in cities. The research in this dissertation improves upon these shortcomings by using disaggregated and detailed databases on water use and the built environment. But of course, the foundations of previous research have informed my work greatly. The following sections review the key variables that influence how water is used in cities.

Key variables

This section reviews the key variables that have been found to significantly affect urban water use. Previous research has documented key variables that influence water use, including an individual's income, household size, water price, weather, housing age, lot size and value, and building type (Arbues et al., 2004; Cavanagh et al., 2002; Gaudin, 2006; Grafton et al., 2011; Hanke & de Mare, 1982; Hewitt & Hanemann, 1995; Kenney et al., 2008; Jones and Morris, 1984; Jorgenson et al., 2009; Lyman, 1992; Olmstead et al., 2003; Polebitski & Palmer, 2010; Renwick & Green, 2000; Rockaway et al., 2011; Syme et al., 2000; Troy et al., 2005). Each of these key variables has been found to be a predictor of water use in cities. I review the demographic, climatic, and built environmental predictors.

Income has been found to be a significant predictor of urban water use: as with nearly all goods and services, water use increases with a corresponding rise in income (Ferrara, 2008; Guhathakurta & Gober, 2007). At least in part, this is because wealthier households are more likely to have water-consuming appliances, swimming pools, and larger lots (Ferrara, 2008). For indoor use, significant differences in personal water habits in households with different incomes have not been found; therefore, indoor usage may be more of a function of square footage of the dwelling and the number of household members (Domene & Sauri, 2006; Ferrara, 2008; Polebitski & Palmer, 2010). Where income has its biggest impact is on outdoor water use. Because outdoor irrigation is a major use of water in many western cities (Arizona Department of Water Resources, 2013; Utah Division of Water Resources, 2010), and lot size and landscaping preferences may be correlated with income, income is a more significant factor during the summer months (Polebitski & Palmer, 2010).

The literature shows that the income elasticity of water use is less than one, ranging from 0.10 to 0.71 (Ferrara, 2008). In other words, water consumption does not increase proportionally with income. Dalhuisen et al. (2003) found in a meta-analysis of residential water demand literature that income elasticity has a mean of 0.43 and a median of 0.24. Renwick and Archibald (1998) estimated that a 10% increase in income led to a 3.6% increase in water use with "low-income households [being] almost five times more responsive to price increases than high-income households." Renwick and Green (2000) estimated that a 10% increase in income will lead to a 2.5% increase in water use. Again, it is likely that income influences outdoor water consumption more so than indoor water consumption. Similarly, income is more likely to be an influence in arid regions where more landscaping irrigation is needed.

Household size

Household size significantly influences water consumption (Arbues et al., 2011; Gaudin, 2006; Wentz & Gober, 2007). Households with more people use more appliances with greater frequency than smaller households. Arbues et al. (2004) found that as household size increases, water use increases, although it was not a proportional increase. For example, a household with two people used less water than a household with four people, but not 50% less. From a review of similar studies, the average elasticity of consumption with respect to household size was between 0.734 and 0.868 (Arbues et al., 2004).

In a residential water use study in Phoenix, household size was not found to be a significant predictor of water usage (Guhathakurta & Gober, 2007). This finding does not necessarily contradict findings of other researchers; rather, it reflects that interior water use is substantially less than outdoor uses. Household size may not influence outdoor water use, after controlling for lot size. Interestingly, Polebitski and Palmer (2010) found that larger household size was associated with improved interior water efficiency, resulting in a per capita savings despite overall household consumption increasing.

Water price

One of the primary interests of researchers is determining the price elasticity of water use (Arbués et al., 2003; Rockaway et al., 2011) in order to determine if pricing strategies are effective as a conservation strategy. The general motivation is to identify strategies to reduce water consumption through pricing mechanisms. In the U.S., there are three main strategies of water pricing: 1) constant rates; 2) increasing block rates; or

3) decreasing block rates. Constant rates charge the same amount of money for each unit of volume used, increasing block rates charge higher rates for higher use, and decreasing block structures charge less for marginal increases in use (Cavanagh et al., 2002). Each of these pricing strategies can be accompanied by a fixed water use charge (Cavanagh et al., 2002).

Most studies indicate that water is an inelastic good. That is, an increase in water price does not proportionally decrease water use (Abrams, 2011; Barkatullah, 1996; Carver & Boland, 1980; Martinez-Espinera & Nauges, 2004; Renwick et al., 1998; Thomas & Syme, 1988; Worthington & Hoffmann, 2008). For example, Renwick et al. (1998) found that a 10% increase in price only reduced water demand by 1.6-2%. Water demand is thought to be inelastic because: it is a basic good that everyone needs; there is no substitute for water; water bills constitute a small portion of household budgets; and price information is delayed or imperfect (Arbues et al., 2004; Balling & Gober, 2007; Cavanagh et al., 2002; Gaudin, 2006).

The elasticity of water demand may be greater over a long time period because water users can adapt to higher prices of water by purchasing water efficient appliances, altering behavior, or planting drought-tolerant landscaping (Arbues et al., 2003; Cavanagh et al., 2002). Furthermore, if pricing information were provided to the user more rapidly or clearly, the elasticity of water may be higher (Arbues et al., 2003; Carter & Milon, 2005; Foster and Beattie, 1979; Gaudin, 2006; Kenney et al., 2008). Elasticity might also be higher for homeowners compared to renters and to low income households (Hoffmann et al., 2006; Renwick & Archibald, 1998), and at different seasons and in different regions (Arbues et al., 2004; Cavanagh et al., 2002; Howe & Linaweaver, 1967;

Kenney et al., 2008; Polebitski & Palmer, 2010; Renwick & Green, 2000).

There should not be confusion, however, as to whether consumers respond to changes in price of water. Even if water demand is somewhat inelastic, it is not totally inelastic. Consumers respond to higher prices, but at a rate less than proportionate to the price increase (Arbues et al., 2011; Renwick & Green, 2000). Block rates have been found to be effective at reducing water consumption (Billings & Agthe, 1980; Cummings et al., 2005; Niewsiadomy & Molina, 1989; Mazzanti & Montini, 2006; Pint, 1999; Renwick & Archibald, 1998; Strand & Walker, 2005), and clear marginal price information on water bills has been shown to reduce water consumption (Gaudin, 2006). When pursued aggressively, block rates can drastically reduce consumption (Michelsen et al., 1999). The evidence clearly indicates that pricing strategies should be part of a suite of conservation efforts.

Weather

Weather is a significant factor in urban water demand. In the summer months as temperatures rise, gardens dry out and households increase outdoor water use. Studies of water use during the summer months have seen increases in water use of 30% to 60% (Cavanagh et al., 2002; Guhathakurta and Gober, 2007; Kenney et al., 2008). For example, in Phoenix, Guhathakurta and Gober (2007) found that two-thirds of residential water use was for outdoor irrigation in the summer. Balling and Gober (2007) found that 40% of annual water use occurs during June, July, August, and September. Despite the seasonal fluctuations in residential water demand, there are few studies that determine elasticities for variables on a seasonal basis, despite the fact that significant differences may exist (Lyman, 1992; Polebitski & Palmer, 2010).

Maidment and Miaou (1986) found that water demand did not increase until temperatures were above 70° in the nine U.S. cities they studied. They found when temperatures rose above 85-90° in Texas and Florida, water use increased 3-5 times per degree. However, other studies only considered temperature effects when the temperatures rose above 90° (Gaudin, 2006). Rockaway et al. (2011) found that an area with an average annual temperature between 50-60° used 16% less water than one with an average temperature of 60°-70°. In Seattle, Polebitski and Palmer (2010) found that a 10% increase in monthly temperature in July and August led to a 10% increase in water usage, but in September and October, a 10% increase in temperature led to only a 4% increase in water use. Other studies have found that the relationship between temperature and water use is nonlinear, where water use increased at a faster rates than temperatures themselves (Guhathakurta and Gober, 2007; Maidment & Miauo, 1986).

Rainfall plays an obvious role in water use. The most important consideration for residential water use is when it occurs and its intensity (Maidment & Miauo, 1986). Polebitski and Palmer (2010) found that a 10% increase in rain in May and June led to a 2.5% decrease in total water usage. They found that rainfall in July and August had very little effect, but it may be because the area they were studying sees very little rainfall during those months. Kenney et al. (2008) found that for every inch of annual precipitation, water use in Colorado decreased by 4%.

Weather variables such as temperature and rainfall drive short-term fluctuations in demand rather that underlying determinants of water use (Abrams et al., 2012). However, finding the right combination of weather variables can be challenging and the impact of weather may be difficult to distinguish from the effects of other management, demographic, and built environmental effects (Kenney et al., 2008). An additional problem facing researchers is the limited availability of data. Water use is typically available only on a monthly basis, but weather changes daily (Kenney et al., 2008).

Housing age

The age of a dwelling can affect water demand, as older homes are more likely to have appliances and fixtures that are less water efficient than newer homes. With older appliances and fixtures, there is likely to be water leakage because of wear and tear (Guhathakuta, 2007; Rockaway et al., 2011). One study estimated that homes built after 1994 use 13 gallon per day less after controlling for the type of household characteristics and appliances (Rockaway et al., 2011). Cavanagh (2002) found that the highest water use occurs when the home is between 20 and 40 years old. The older the home, the more likely the homeowner will have replaced their outdated appliances and fixtures.

Lot size

Households on large lots, on average, have higher water use (Abrams et al., 2012). Larger lots usually mean larger lawns, more vegetative cover, and larger houses. Therefore, lot size has a positive correlation to water use (Balling & Gober, 2007; Blokker, Vreeburg, & van Dijk, 2010; Guhathakurta and Gober, 2007; Polebitski & Palmer, 2010; Renwick & Green, 2000). Guhathakurta and Gober (2007) found that controlling for other variables; lot size had the greatest impact on water use. With each 1,000 square foot increase in average lot size, monthly water use increased by about

1.8%. Renwick and Green (2000) found that with a 10% increase in lot size water demand increased by 2.7%.

Type of building

Troy et al. (2005) explored the water consumption profiles of households living in different forms of residential development in a range of locations across Sydney, Australia. In particular, they sought to understand how different types of dwellings—separate houses, semidetached houses, and flats—were related to household water use. An overall finding of the research was that the per capita consumption of water is, for all practical purposes, the same for people living in traditional houses as it is for the residents of high density dwellings.

Methods of modelling water use

There are at least 40 years of research on modelling urban water use. Throughout all this research, there appear to be three common purposes: to determine how the price of water will affect water use (Brookshire et al., 2002); to use demand models to predict usage in the future; and to identify the determinants of water use (Donkor et al., 2012). In order to accomplish the third purpose, many researchers have developed multivariate statistical models that relate water consumption to a variety of independent variables. Ordinary least squares regression, generalized least squares, two and three stage least squares, logit, and instrumental variables have all been used to model water use, but ordinary least squares regression "dominates the literature" (Worthington & Hoffmann, 2008).

Many researchers have used multivariate regression to identify the determinants of urban water use (Agthe & Billings, 1980; House-Peters & Chang, 2011; Maidment et al., 1985; Nauges & Thomas, 2003; Polebitski & Palmer, 2010; Syme et al., 2004). Multivariate regression has been useful for short-term forecasting, identifying the elasticity of price, and assessing the important determinants of demand (House-Peters & Chang, 2011). Studies employing multivariate regression were limited by the availability of spatially disaggregated databases, parcel scale building attributes, and remotely sensed land cover data.

Other modeling methods include simultaneous equation demand modeling (Espey et al., 1997), artificial neural networks (Adamowski & Karapataki, 2010; Herrera et al., 2010), and system dynamics models (Rosenberg et al., 2007). These modeling techniques were found to generate highly accurate predictions of short-term demand, as well as proving useful for visualizing how variables interact to influence water demand. However, both methods are data and computationally intensive (House-Peters & Chang, 2011).

Scale of analysis

Data availability is a crucial component of every study on water use. The scale of analysis tends to determine what type of data is available and the availability of data often determines the researcher's scale of analysis. The most common studies are at the city, municipality, or county scale (Balling & Gober, 2007). More recently, studies have been conducted at the household level (Shandas & Parandvash, 2010), while very few studies have been conducted at the neighborhood scale (Adamowski & Karapataki, 2010;

Larson et al., 2013) (Table 1).

Data sources

The primary data source for aggregate studies on water demand is public utility records (Adamowski & Karapataki, 2010; House-Peters et al., 2010; Michelsen et al., 1999; Qi & Chang, 2011). United States Geological Survey (USGS) 5-year estimates of water use by county are another data source utilized by researchers examining aggregate water use (http://waterdata.usgs.gov/nwis). National weather service reports have been used to determine climatic variables at aggregated scales (Foster & Beattie, 1979; Michelsen et al., 1999). National surveys such as those from the American Water Works Association (AWWA) are used for comparative studies that examine differences between cities (Foster & Beattie, 1979; Sohn, 2011).

Public utility records are the most common source of water use data for disaggregated studies (Fox et al., 2009; House-Peters et al., 2010; Shandas & Parandvash, 2010). Tax assessor records are used to determine the physical characteristics of properties (Fox et al., 2009; Shandas & Parandvash, 2010). Mail surveys have been used to determine how key variables affect water use for individual water use (Hurd, 2006). Hurd (2006) mailed 423 surveys to residents in Albuquerque, Las Cruces, and Sante Fe to determine landscape preferences, level of education, number of children, and the degree to which people feel responsible for using water. These are valuable variables that cannot be ascertained from other sources. Mail surveys have also been used to determine water use at the household level (Blokker, Vreeburg, & van Dijk, 2010; Herrera et al., 2010).

Sometimes automated daily data loggers attached to household water meters have been used to measure water use at the household level. Olmstead et al. (2007) placed 1,082 automated loggers in 11 cities across the western U.S. to estimate price elasticities of water use under different price mechanisms. The automated data loggers provided daily measurements of water use at the household level.

Conservation actions considered

While the first portion of this dissertation will focus on modeling water demand, the conclusions and recommendations will emphasize water conservation options. Broadly, conservation strategies fall into two categories, pricing strategies, and nonprice strategies. Pricing strategies generally employ higher water prices as a means of reducing demand (Renwick & Archibald, 1998). Nonprice conservation programs (from Michelsen et al., 1999) include public information programs, education programs, retrofit programs, ordinances and regulations.

Categorized slightly differently, conservation or non-price strategies normally take one of three forms: 1) public education programs such as public awareness campaigns and clearly marked water bills; 2) technology improvements such as low flow fixtures and shower heads, and water efficient appliances; and 3) water restrictions that limit the hours that water can be used for irrigation (Grafton et al., 2011). Though nonprice strategies can reduce water usage, it is difficult to differentiate between the effectiveness of different programs as there often multiple nonprice programs happening at the same time (Kenney et al., 2008; Michelsen et al., 1999).

Research on nonprice conservation strategies has found that mandatory water restrictions were effective at reducing water usage, sometimes resulting in over 30% cuts to water use (Kenney et al., 2004; Kenney, 2008; Lee 1981; Renwick & Green, 2000; Shaw & Maidment, 1987). Analysis of water restrictions in Santa Barbara and Goleta California found that the average household used 16% less water in Santa Barbara and 28% less water in Goleta when mandatory water restrictions were in place (Renwick & Archibald, 1998). The authors go on to argue that achieving reductions of water demand of 15% or more would require additional water restrictions or larger price increases. Espineira and Nauges (2004) found that 1 hour of water restrictions per day was similar to the effects of a 9% increase in the price of water. However, another study in Corpus Christi, Texas found no significant effect on water usage when the water restrictions were imposed during a drought (Cavanagh et al., 2002).

A survey of three cities in New Mexico found that when the respondents were made aware of water conservation, they were 13% more likely to adopt a landscape that was more water efficient (Nieswiadomy & Molina, 1989). Nieswiadomy and Molina (1989) found that public education was higher in the arid West, but when taking all four regions of the United States together, nonprice programs were not effective. One analysis of the effect of conservation programs on water use in California found landscape programs and watering restrictions significantly reduced water outdoor water use, but not indoor use (Corral, 1997).

Limitations of existing literature

Many important findings have been established over the past 40 years of research on urban water use. However, there are omissions or shortcomings to many of these studies that leave questions unanswered, warranting further research on water demand

(Jorgensen et al., 2009). This section reviews limitations of existing research in order to demonstrate that further research is needed.

Most studies have been grouped water demand determinants into socioeconomic and climatic variables (Adamowski & Karapataki, 2010). Lot size was measured when available, but more detailed measures of the built environment were omitted from most studies. When built environment variables have been considered, they have been found to be significant drivers of urban water use (House-Peters & Chang, 2011). This dissertation will utilize the detailed measures of the built environment at both the parcel and neighborhood scale.

Another omission from the majority of water demand studies is the water use of urban land uses other than single-family households (House-Peters & Chang, 2011; Larson et al., 2013; Michelsen et al., 1999; Olmstead et al., 2007). Single-family households dominate the landscape of cities, but to exclude commercial, semiattached, and apartment buildings is to ignore significant shares of the total urban water use budget. In the following chapter, I show that the single largest water users in Salt Lake City were industrial and institutional organizations. This dissertation will examine multiple urban land use types and their associated water use.

Many studies rely on aggregated data (Adamowski & Karapataki, 2010; House-Peters et al., 2010; Michelsen et al., 1999; Qi & Chang, 2011) and therefore, important subtleties of water use are lost. Aggregation of data is therefore a potential barrier to understanding the major drivers of urban water use. Of particular concern is when researchers use aggregated variables to measure disaggregate water use, introducing aggregation bias and the ecological fallacy. If the data are available for disaggregate analysis, the research will likely be more accurate and valid to demonstrate a variable's effect on water use.

A final shortcoming of all studies on water demand is the omission of key variables. Some studies omit demographic or built environmental variables (Adamowski & Karapataki, 2010; Balling & Gober, 2007; Foster & Beattie, 1979), while others omit climatic variables (Qi & Chang, 2011; Shandas & Parandvash, 2010). The unavailability and subsequent omission of key variables that have been found to influence urban water use makes the results of these studies fall short. Some variables may be reported to be more important than others without controlling for known key influences. The research in this dissertation will attempt to gather as many key variables as possible.

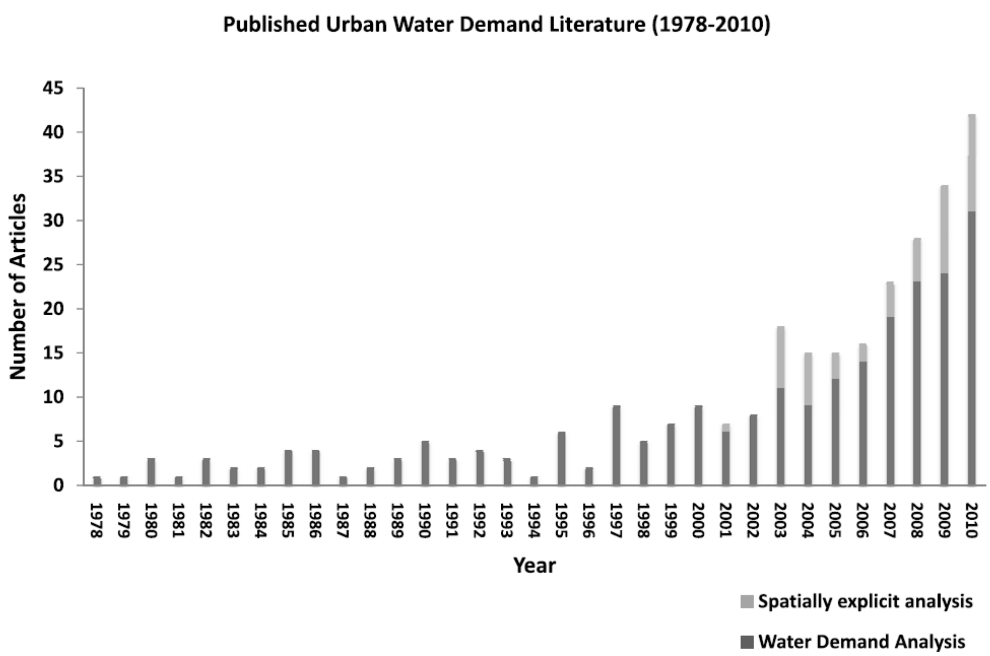

Figure 6 Published urban water demand literature (from House-Peters & Chang 2011)

Table 1 Scales of water demand analysis

Household	*Neighborhood*	*City or County*
Blokker, Vreeburg, & van Dijk, 2010; Fox et al., 2009; Olmstead et al., 2007; Shandas & Parandvash, 2010.	Adamowski & Karapataki, 2010; House-Peters et al., 2010; Larson et al., 2013.	Balling & Gober, 2007; Foster & Beattie, 1979; Michelsen et al., 1999; Qi & Chang, 2011; Sohn, 2011;

CHAPTER 3

DRIVERS OF URBAN WATER USE

In this chapter, I develop water demand models for four urban land use types that relate the built environment, climate, and demographics to annual water use. These models are developed based on a case study of Salt Lake City, Utah. The key contribution of this chapter is to demonstrate the effects of the built environment on urban water use. In each of the estimated models, built environment characteristics improve the model fit. This research is an improvement on previous research in three ways. First, it is based on disaggregated water demand analysis with a very large sample size. The database includes 77,256 parcels in Salt Lake City, Utah, with water use, location, and urban land use type specified for each. Secondly, the research identifies water demand differences between urban land uses in a city. Knowing these differences should help make more accurate predictions of future water demand. Third, where data availability constrains much of the past research on water demand (Gaudin, 2006), I have compiled a rich database that includes climatic, built environment, and demographic data for the parcels in our database. These results may inform the design of land-use regulations to promote water conservation.

I ask:

1. What is the relative importance of demographic, built environment, and climate variables on water use?
2. How do characteristics of the built environment affect urban water use?
3. How does water use vary by urban land use type?
4. Does the relative importance of demographic, built environment, and climatic variables change for common urban land use types?

Conceptual framework

I hypothesize that water use varies by urban land use type, and is a function of climate, demographic, and built environmental variables. These hypotheses are based on findings from existing studies. I hypothesize the relationships as follows:

Climate: I hypothesize climate variables such as seasonality, precipitation, and temperature affect water use. Water use will be higher in the summer and warmer drier weather is associated with more water use (Abrams et al., 2012; Kenney et al., 2008; Maidment & Miauo, 1986; Polebitski & Palmer, 2010; Worthington & Hoffmann, 2008). In this chapter, I explore the effects of both seasonal and intraseasonal variations on water use.

Built Environment: I hypothesize that the year built, the lot size, the number of stories, the total number of rooms, and the number of bathrooms and kitchens all influence water use. Lot size has been found to have a large impact on water use (Abrams et al., 2012; Guhathakurta and Gober, 2007). Larger lots have larger lawns, more vegetative cover, more bathrooms and appliances, and therefore lot size has a positive correlation with water use (Balling & Gober, 2007; Blokker, Vreeburg, & van Dijk, 2010; Guhathakurta & Gober, 2007; Polebitski & Palmer, 2010; Renwick & Green, 2000). The year a building was built likely affects water use, where older buildings tend to use more water (Guthathakuta & Gober, 2007; Rockaway et al., 2011). I anticipate that additional rooms, kitchens, and bathrooms will increase water use.

Demographics: I hypothesize that demographics such as income, household size, and whether a resident rents or owns a property influences water use. I use proxy measures for household size and income, i.e., number of bedrooms and assessed value of the property respectively. I anticipate that residents who own will have higher income, and therefore have a larger property size and use more water (Domene & Sauri, 2006; Ferrara, 2008). I hypothesize, but cannot test, that individual's attitudes, preferences, and values also affect water use. Lack of data on individual preferences prohibits this analysis.

Methods

This section details how I gathered data and estimated models for a case study of Salt Lake City, UT. While the results and data are unique to this case study, the methodology could be applied in different regions if data availability is not a constraint. Data availability is a challenge, as public utility records at the parcel level limited this analysis to a single city. For the analysis, I created a dataset that includes climatic, built environment, and demographic variables for 77,235 parcels in Salt Lake City, Utah, in 2011.

Study site: Salt Lake City, Utah

Salt Lake City is the capital city of Utah and is the principal metropolitan center of the state. Of the 50 states, Utah ranks 49th in the U.S. for highest annual precipitation but 2nd in the U.S. for highest per-capita water use (UDWR, 2010). Salt Lake City has effective rainfall during the growing season equivalent to other major urban areas in the desert southwest, including Phoenix and Albuquerque (UDWR, 2009; UDWR, 2010). The Salt Lake City Department of Public Utilities is the primary municipal water provider for Salt Lake City and delivers more than 22 billion gallons each year (UDWR 2009). On average, residential consumers use 62.7% of the supply (42,652.9 acre-feet, 13.9 billion gallons), commercial consumers use 21.8% (14,841.2 acre-feet, 4.8 billion gallons), institutional consumers use 11% (7,507.1 acre-feet, 2.4 billion gallons), and industrial consumers use 4.4% (3,018.6 acre-feet, 0.98 billion gallons). Over half (65%) of all residential water use occurs outdoors and 35% of residential use occurs indoors (UDWR, 2009).

The built environment of Salt Lake City is dominated by single-family residential properties. A commercial core runs through the center of the city, and joins the downtown region with the suburbs of the city. Large institutions, such as the Latter Day Saints church, the international airport, and the University of Utah, are the major employers in the region. There is a preference for lawns and well-manicured front lawns in many parts of the city. As such, the city is very green, while the surrounding natural environment is very dry and brown.

Salt Lake City's water supply system is fed by surface water from the nearby mountains and from wells tapping groundwater (US EPA, 2010). The Utah Division of

Water Resources predicts that urban demand will soon outstrip this supply system. According to UDWR, the Salt Lake City Public Utilities Department will serve a customer base of 391,989 by 2030 (a 31.5% increase from 2005) and a customer base of 504,844 by 2060 (a 69.4% increase from 2005) (UDWR, 2010). Even accounting for incremental conservation achievements (reaching a 25% usage reduction by 2050), these growth figures indicate that Salt Lake City will use more than 88,000 acre-feet of water by 2030—with a supply deficit of more than 44,000 acre-feet (14.5 billion gallons)—and will use more than 100,000 acre-feet of water by 2060—with a supply deficit of more than 56,000 acre-feet (18.5 billion gallons). Water sustainability will be a critical issue in Salt Lake City.

Data

I collected key climatic, demographic, and built environment data at the parcel level for Salt Lake City, Utah, in 2011. The dataset was built from the following data sources:

1. The Salt Lake City Public Utilities database provided monthly water use for all customers of the Salt Lake City public utility (n=88,245). I aggregated accounts to each parcel level because the parcel was the unit of analysis. Included in this database were building locations (addresses), urban land use type (single family, apartment, industrial, restaurant, triplex, duplex, fourplex, business) and monthly water use. After cleaning the database for missing values and incorrectly coded parcel identifications, I used 77,256 parcels for analysis.

2. The Salt Lake County Assessors database provided built environment and

demographic variables for parcels in the Salt Lake City Public Utilities database. I joined information tables from this database to the public utilities database based on matching parcel numbers.

3. The PRISM Climate Group Data (PRISM Climate Group, 2004) provided climatic variables for the Salt Lake City region. The PRISM (Parameter-elevation Regressions on Independent Slopes Model) Climate Group developed a dataset that uses point measurements of precipitation, temperature, and elevation to produce continuous, digital grid estimates of monthly and yearly climatic parameters. Temperature and precipitation vary across the Salt Lake Valley from low in the valley to high on the benches; therefore, I need continuous measures of temperature and precipitation.

4. Remote sensing data were used to calculate land-cover information for each parcel in the Salt Lake City Public Utilities dataset. The Utah State geodata portal (AGRC) provided Light Detection and Ranging (LiDAR) data acquired in 2006 for most of the greater Salt Lake City metropolitan area in 2006. In order to generate vegetation cover variables for the water use models, two different land-cover classifications were used. For the first, four-band NAIP imagery using a Maximum Likelihood classifier was used to create a binary vegetation/nonvegetation classification. These data were then combined with a canopy map derived from LiDAR first-minus last-return for a four-class land cover map of nonvegetation, ground vegetation, ground vegetation overlapped by tree canopy, and nonvegetation overlapped by tree canopy. For the second, using a support vector machines (SVM) classifier, the four-band NAIP imagery was classified together with three LiDAR-derived layers: first-return minus bare-earth (indicates high surfaces), first- minus last-return (indicates tree canopy), and last-return minus bare-earth

(indicates building rooftops). I digitized polygons of training and validation data (~3000 pixels total; ~50 pixels per polygon) throughout the study area from the NAIP imagery using ESRI ArcGIS 10.0 software. All classifications were performed using ENVI 4.3 image processing software. Classification accuracy was assessed to be greater than 88.9% in all classes. I used GIS tools to calculate the fraction of turf cover and canopy cover of every parcel in Salt Lake City.

Measures

The dependent variable for this chapter was annual water use for each parcel in Salt Lake City in 2011. Annual use is measured in gallons. I measured the effect of the following variables on annual water use.

Climatic Variables: Temperature was measured in degrees Celsius x 100 and was the average daily maximum temperature for 2011. Precipitation was measured in millimeters, and was the average daily precipitation for 2011.

Built Environment Variables: I used the following variables from the tax assessors database to measure characteristics of the built environment: number of bedrooms, number of kitchens, total bathrooms, lot size measured in acres, the year the building was built, number of units in a building, number of stories in a building, and number of lots on a commercial property. Based on the remotely sensed data, I measured turf fraction as the percentage of turf that was covering a parcel. I measured the tree fraction as the percentage of the fraction that was covered with trees.

Demographic Variables: I used the assessed value of the building and property as a proxy measure for income, where I assumed the higher the value of the property and building, the higher the income of the resident. I measured the tenure of the building as a binary option; either the property is renter or owner occupied (from the assessor's database). I measure the number of families in each building from the tax assessor's data. I also use the number of bedrooms as a proxy measure for household size.

Modelling

I used ordinary least squares (OLS) regression to identify the key drivers of urban water use in Salt Lake City, Utah. The dependent variable was not normally distributed, so I used the natural log of annual water use as the dependent variable. The independent variables used in the models were not statistically correlated, and the dependent variable was a continuous measure. In order to ensure that the independent variables were in fact independent, I measured tolerance values (T) for each variable. Tolerance values reflect the degree of collinearity in the models, where high values (on a scale of 0 to 1) indicate that no collinearity exists. I minimized collinearity in our models by omitting variables that were found not to be independent.

I estimated models for four types of urban land use: single family residential, semiattached housing (duplex, triplex, and fourplex), apartments, and commercial (businesses and restaurants). I isolated the contribution of climate, built environment, and demographic variables by presenting three models per land use type. For example, model 1= climate only, model 2 = climate + built environment; model 3 = climate + built + demographics. The percentage of variance explained were indicated by R^2 values, which range from 0.00-1.00. High values indicate a good model fit. I included both significant and nonsignificant variables because the research questions are hypothesis testing, and to show the importance of the variable.

The coefficients in the model indicate the direction of effect as well as the magnitude of effect. I also present standard errors for the coefficient values of each value. The size of the standard error indicates the variation of the coefficient values. Finally, for each variable I provided *p* values to indicate the probability that the coefficient was statistically significantly different than zero. I used a 95% confidence interval to determine if coefficients were statistically significant.

Case study results

In this section, I applied the data gathering methodology to estimate models of urban water demand. I begin the analysis with descriptive statistics for water use by urban land use types. I compared annual water use amongst urban land use types to identify significant differences. For all urban land use types, average water use in Salt Lake City was highest in the summer months starting in June, peaking in September and declining in November. Winter use was stable and lower than the summer months (Figure 7).

I found that industrial accounts had the highest mean annual use, averaging over 16 million gallons a year. Hospitals had the next highest mean annual use of water at over 14 million gallons a year followed by schools, churches, and charities at almost 4 million gallons per year. Single family residences had the lowest mean annual use averaging about 148,000 gallons per year, but had the greatest cumulative contribution to water use in Salt Lake City, using more than 9 billion gallons of water in 2011. Businesses and restaurants were also intensive water users, with high mean annual use per acre and high total use (Table 2). Mean use per acre is indicated in Table 2.

An analysis of variance (ANOVA) test revealed that mean annual water use was significantly different among the urban land use types (F 307.738; p= <0.001). The variance between groups was homogenous (Levene Statistic= 763.198; p= <0.001), so I used Bonferroni Post Hoc tests to identify which urban land use types had statistically significant different annual water use. Apartments and parks had no statistically significant differences in mean annual water use, nor did businesses and restaurants. Duplexes, triplexes, fourplexes, and single-family residences did not have statistically significant different mean annual water use and hospital and industrial users did not have statistically significant mean annual water use. Other comparisons of urban land use types indicated significant differences among mean annual water use.

The data revealed that conservation efforts have the potential to reduce water use substantially (Table 3). Table 3 shows theoretical reductions in water use if conservation efforts achieved a 10, 25, and 50% reduction in use. The values were calculated for all user accounts at a 10, 25, and 50% reduction in current use. The table also indicates that the savings if only the top 10% highest users were targeted for conservation. These data indicate that theoretically millions of gallons of water can be saved by water conservation, as much as 10 billion gallons in a year.

Single family residential models

Table 4 presents the estimated models for single-family residential parcels. Almost all variables were significant, and I minimized collinearity. The F statistic in each model was significant. Climatic variables explained a very low percentage of the variance in the data ($r^2 = 0.132$), while the built environment variables substantially improved the model's fit to the data. The number of bedrooms, number of kitchens and bathrooms, and the higher the fraction of turf and tree cover were all associated with higher water use. The greatest effect on water consumption for single-family residences was the size of the lot (acres), where larger lot sizes were associated with higher water use. Income significantly influenced water use, where higher income was associated with higher water use. The year the building was built indicated that the more recent the building, the higher the water use. Whether the parcel was owner occupied was not significant in the fully specified models.

Since the primary use of water is for outdoor irrigation, I estimated models of average outdoor water use (Table 5). The public utility data do not measure outdoor use, so I had to make the assumption that all water used in the winter was for indoor use. This is a safe assumption in Salt Lake City, as snow covers the ground most of the winter and no vegetation is growing. I calculated the average indoor monthly use, and subtracted this value from the monthly use in the months when irrigation is possible (April-October). The average of this difference was average outdoor water use, and I use the natural log of average outdoor water use as the dependent variable to meet the assumptions of OLS. The results are presented in Table 5 and provide empirical evidence that the physical characteristics of properties influence outdoor water use: Specifically: the more turf and tree fraction, the more water used; the newer the house, the more water; and if it is owner occupied, the higher the water use.

I estimated models for indoor water use, and the models explained a very low percentage of the variance in indoor water use; however, variables that were hypothesized to influence indoor water use such as the year built, owner occupied, total acres, total bathrooms, and number of kitchens all were significant influences on indoor water use. Some key variables were excluded because they did not theoretically relate to outdoor water use, i.e. number of bathrooms and number of bedrooms.

Semiattached residential models

The semiattached residential parcel models included parcels that were duplexes, triplexes, and fourplexes. Table 6 presents the results of the estimated models. The F statistic in each model was significant at $p<0.001$. The climatic variables were significant but temperature did not exhibit an anticipated positive coefficient and the two variables did not explain the data well. When built environmental variables were added, the model fit improved. Again, lot size was associated with higher water use, as were the number of kitchens and bedrooms.

Whether a semiattached residential unit was owner occupied was again not significant. The number of families living at the parcel was significant, and more families were associated with higher water use. Finally, income was a significant variable, with water use increasing as the assessed value increased. The number of bathrooms was found to be collinear with other predictor variables.

I was interested in how these variables influenced outdoor water use. I estimated a model of outdoor. The results were similar to the single-family residential properties, where the greatest influence on outdoor water use is the amount of the property that is covered by turf grass. The primary difference was that the amount of the property that was covered by trees was not significant.

Apartment demand models

Again, the climate variables were significant, though temperature did not exhibit the anticipated direction of effect (Table 7). Alone, the climatic variables did not explain more than 4% of the variance in the data. When built environment variables were added, the model fit improved substantially. The number of units and number of stories were both significant, and more units and more stories were associated with greater water use. Newer apartments also used more water. When demographic variables were considered, the final value of the parcel was significant, but the higher the final value, the lower the water use. For outdoor water use, the fraction of the parcel covered by turf was a significant influence on use; however, the percentage of the parcel covered by trees was not.

Commercial water demand models

For the estimated commercial property water use models, the climatic variables did not explain the variation in the data as well. I chose not to separate businesses and restaurants in order to better measure how commercial properties on a whole used water. Built environment variables explained much more of the variation in water use (R^2=0.369), where large parcels with a many lots were associated with higher water use. Neither turf nor tree fraction were significant in these models. When building values were added, water use for commercial buildings increased as the final value of a parcel increased and the direction of effect of lot size changes (Table 8).

Discussion

The data clearly indicate that seasonal climate conditions were the primary drivers of water use in Salt Lake City (Figure 7). The mean monthly water use increased dramatically during the summer months, as irrigation was required for outdoor landscaping By contrast, winter water use dropped substantially because snow cover and cold temperatures made outdoor irrigation unnecessary and almost all water use was for indoor purposes. I can therefore assume that seasonal variations in temperature and precipitation are a primary driver of water use across all service types in Salt Lake City, where warm and dry summer temperatures led to more water use for outdoor irrigation during this time. This finding was also demonstrated by the UDWR (2009) in their analysis of water use across Utah.

The urban land use types that had the highest mean water use in Salt Lake City were industrial and hospital accounts (Table 2). Though few in number, these users had the highest mean annual use, and one industrial account had the highest total annual use, using over 596 million gallons of water in a year. The need for this much water was likely a result of the type of industry using the water: in the case of Salt Lake City, the largest user is an oil refinery. Cumulatively, however, single-family residential buildings used over 9,593 million gallons of water in 2011, indicating that single-family urban land use had the highest total water use in the region (Table 2).

The results of the ANOVA tests revealed that different urban land uses have different water consumption patterns. Most urban land use types differed in mean annual water use, but some groups of land use types did not differ in annual use. For example, duplexes, triplexes, fourplexes, and single family residences did not differ in mean annual water use. Similarly, businesses and restaurants did not differ in mean annual water use. These findings indicate that for estimates of future water demand, some urban land use types can be expected to use similar amounts of water on average regardless of their climate, built environmental, or demographic characteristics.

While seasonal conditions were found to be the primary driver of water use, climatic variation across the Salt Lake Valley did not prove to be important drivers of urban water use. Consider that none of the climate-only models fit the data very well (R^2 between 0.01 and 0.132). While both temperature and precipitation were almost always significant in the models, the direction of effect was mixed and counterintuitive. For example, whenever the coefficient for temperature was a negative or the precipitation coefficient was positive, the model indicated that the cooler and wetter temperatures led people to use less water. This was counterintuitive; indeed it is not likely that people use less water when the weather is hot and dry. Rather, this result indicated that intraseasonal variation across the Salt Lake Valley was not a consistent driver of water use. The constant in these models is very high, indicating a high level of base water use that fluctuates based upon slight variations in temperature and precipitation.

In all the models (Tables 4-8), the model fit improved substantially when built environmental variables were included. The commercial water use model had a R^2 of 0.02 with only climate variables, and increased to 0.369 when built environment variables were added. This effect was observed in each of the urban land use types, and is a strong indication of the importance of the built environment on water use. Demographic variables contributed very little to improved model fit. I suggest that the most important finding of this chapter is that the characteristics of the built environment and the type of urban land use are important influences on urban water use in Salt Lake.

The characteristic of the built environment that had the greatest effect on water use was the size of the parcel. In each of the urban land use types, the larger the lot, the more water was used. Our findings are similar to Guhathakurta and Gober (2007), who found that controlling for other variables, lot size had the greatest impact on water use, where with each 1,000 square foot increase in average lot size, monthly water use increases by about 1.8%. Renwick and Green (2000) found that with a 10% increase in lot size water demand increases 2.7%. These collective results point strongly to the impact of lot size on water use. The other major drivers of urban water use in Salt Lake City were the number of bedrooms, kitchens, and bathrooms. The role of land cover characteristics such as the fraction of the parcel that is covered by turf and trees warrants further research. For example, for single-family buildings (Table 3), more tree cover was associated with higher water use, while the opposite was found for semiattached buildings (Table 6).

Summary

This chapter used a detailed database to analyze urban water use in Salt Lake City, Utah, for the year 2011. I compared water use by urban land use type, and developed models that related the climatic, built environment, and demographic variables to water use. Not surprisingly, I found that seasonality was the greatest driver of water use, where in the summer, outdoor irrigation increases average water use for all urban land use types. Accounting for this, however, I found that certain urban land use types used more water than others, where industrial users and hospitals used the most water.

Single-family residential units had the lowest mean annual water use, but their cumulative use as a land use group showed the highest total water use. The data indicate that different urban land use types exhibit different water consumption patterns, but certain urban land use types do not differ in average annual use. For example, single family, duplex, triplex, and fourplex accounts use similar amounts of water in a year. Parks and apartments do as well. However, for other comparisons, significant differences exist.

The models showed the relative contribution of climate, built environment, and demographic variables on urban water use. Climatic variables alone explained very little of the variation in water use for all urban land use types. When built environment variables were added to the models, the model fit improved significantly and the models indicated that variables such as lot size, tree and turf fraction, the number of bedrooms and kitchens, and the year built all significantly affected water use. Larger lot size was associated with a greater amount of water used. The demographic variables I was able to gather contributed very little explanation for water use in any of the urban land use types.

The results of this chapter indicated which parcel-level characteristics influence water use, but it is likely that there are characteristics of neighborhoods that influence water use as well. The next chapter of the dissertation builds upon this chapter by exploring if there are neighborhood characteristics that influence parcel scale water use. For example, there may be attitudes or norms that are shared between neighbors that influence water use, such as landscaping preferences. Or, the age of the neighborhood may be influence parcel-level water use because of the age of the water infrastructure in and between the parcels. If there are neighborhood characteristics that affect parcel-level water use, it may help explain the spatial clustering of high and low water use in cities. These lines of inquiry are addressed in the following chapter.

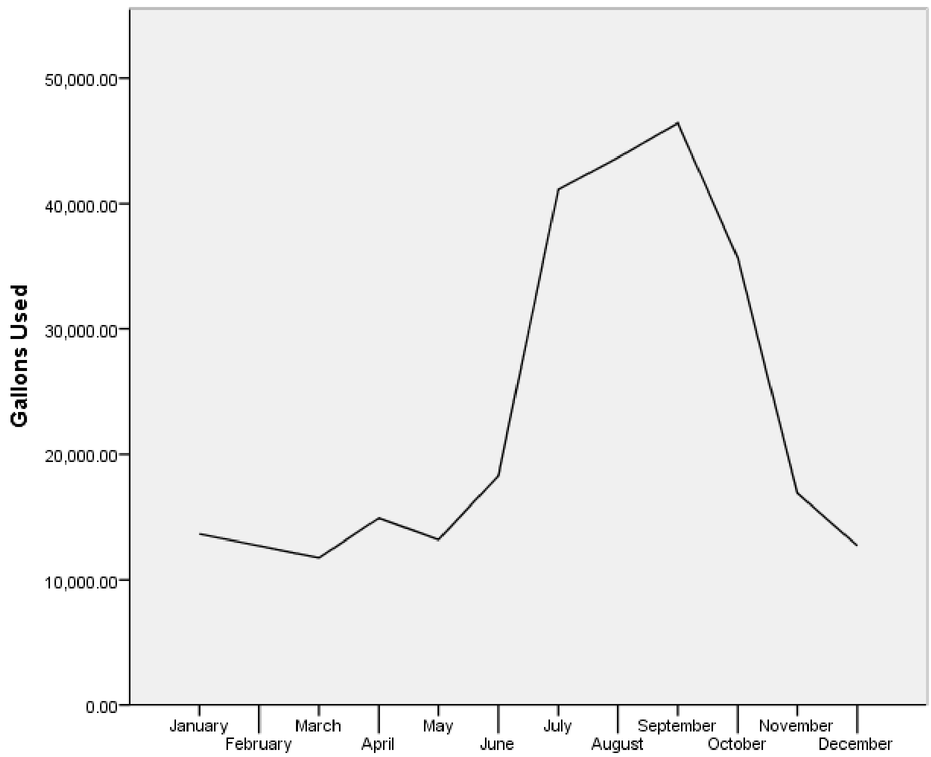

Figure 7 Water use by month in 2011 (all urban use types)

Table 2 Annual water use (million gallons) by service type

Service Type	Total	Mean	Maximum	Mean Acres	Mean Use Per Acre	Total Cases
Apartment	2,141.6	2.1	41.6	1.12	17.6	1,041
Business	4,513.1	1.0	154.0	1.84	2.5	4,364
Duplex	722.6	0.2	1.4	0.18	1.1	4,351
Triplex	94.8	0.2	1.0	0.17	1.3	493
Fourplex	285.4	0.3	1.6	0.20	1.8	1,006
Hospital	175.9	14.7	81.2	1.35	5.8	12
Hotel or Motel	513.3	6.0	78	0.47	9.0	85
Industry	1,397.6	16.1	596.4	3.62	2.6	87
Miscellaneous	705.7	3.9	204.3	4.80	8.3	181
Parks & Municipals	204.6	1.6	31.9	6.77	1.8	125
Restaurant	139.8	0.9	4.6	0.43	5.3	164
School/Church	1,220.3	4.0	453.0	2.86	29.7	306
Single Residential	9,593.3	0.1	4.6	0.22	0.8	65,041

Table 3 Theoretical water conservation in Salt Lake City, in millions of gallons

Conservation Target	**Water Conserved**	**Water Conserved by Top 10% of Water Users**
10%	2,170	1,270
25%	5,430	3,180
50%	1,090	6,350

Table 4 Water demand models for single-family residences

Variable	B	St. Error	Sig	Tolerance
		Climate		
Constant	12.539	0.368	0.000	
Temperature	-0.002	0.000	0.000	0.430
Precipitation	0.001	0.000	0.000	0.430
R^2				0.132
		Climate with Built Environment		
Constant	3.171	0.403	0.000	
Temperature	0.003	0.000	0.000	0.336
Precipitation	0.002	0.000	0.000	0.305
Owner Occupied	0.059	0.019	0.002	0.969
Number of Bedrooms	0.081	0.005	0.000	0.585
Number of Kitchens	0.063	0.026	0.017	0.980
Total Bathrooms	0.115	0.007	0.000	0.466
Turf Fraction	-0.690	0.149	0.000	0.191
Tree Fraction	-0.017	0.154	0.912	0.529
Acres	1.575	0.112	0.000	0.126
R^2				0.313
		Climate with Built Environment and Demographics		
Constant	3.762	0.643	0.000	
Temperature	0.002	0.000	0.000	0.396
Precipitation	0.001	0.000	0.000	0.332
Owner Occupied	0.030	0.026	0.256	0.977
Bedrooms	0.073	0.006	0.000	0.622
Kitchens	0.077	0.033	0.019	0.975
Total Bathrooms	0.068	0.009	0.000	0.398
Turf Fraction	0.51	0.196	0.793	0.214
Tree Fraction	0.290	0.207	0.162	0.506
Acres	0.929	0.147	0.000	0.125
Final Value	0.000	0.000	0.000	0.303
Year Built	0.000	0.000	0.094	0.951
R^2				0.276

Table 5 Physical properties of single-family residential properties on outdoor water use

Variable	Coefficient	St. Error	p value	Tolerance
Constant	-230.78	1.115	0.000	
Temperature	0.007	0.000	0.000	0.346
Precipitation	0.004	0.000	0.000	0.326
Owner Occupied	0.257	0.033	0.000	0.973
Turf Fraction	1.982	0.117	0.000	0.808
Tree Fraction	2.655	0.192	0.000	0.907
Year Built	0.007	0.000	0.000	0.553
R^2				0.295

Table 6 Water demand models for semiattached residential

Variable	B	St. Error	Sig	Tolerance
		Climate		
Constant	18.581	1.156	0.000	
Temperature	-0.004	0.001	0.000	0.522
Precipitation	0.000	0.000	0.003	0.522
R^2				0.010
		Climate with Built Environment		
Constant	2.48	1.875	0.185	
Temperature	0.002	0.001	0.006	0.389
Precipitation	0.001	0.000	0.000	0.369
Bedrooms	0.080	0.009	0.000	0.840
Kitchens	0.086	0.020	0.000	0.911
Year Built	0.002	0.001	0.001	0.686
Turf Fraction	1.588	0.619	0.010	0.411
Tree Fraction	-1.548	0.451	0.001	0.661
Acres	2.016	0.326	0.000	0.311
R^2				0.173
		Climate with Built Environment and Demographics		
Constant	60644	1.983	0.001	
Precipitation	0.000	0.000	0.721	0.262
Temperature	0.000	0.001	0.782	0.323
Bedroom	0.058	0.010	0.000	0.762
Kitchens	0.055	0.024	0.021	0.649
Year Built	0.002	0.001	0.000	0.678
Turf Fraction	1.851	0.613	0.003	0.438
Tree Fraction	-1.224	0.448	0.006	0.655
Acres	1.157	0.345	0.001	0.273
Owner Occupied	-0.003	0.025	0.918	0.909

Table 6 continued

Variable	B	St. Error	Sig	Tolerance
		Climate with Built Environment and Demographics		
Families	0.079	0.024	0.001	0.627
Final Valuation	0.000	0.000	0.000	0.459
R^2				0.193

Table 7 Water demand models for apartments

Variable	B	St. Error	Sig	Tolerance
		Climate		
Constant	48.66	5.335	0.000	
Temperature	-0.019	0.003	0.000	0.486
Precipitation	-0.002	0.001	0.000	0.486
R^2				0.081
		Climate with Built Environment		
Constant	-7.643	2.645	0.004	
Precipitation	-0.001	0.000	0.115	0.962
Number of Units	0.002	0.00	0.000	0.917
Number of Stories	0.314	0.034	0.000	0.981
Year Built	0.011	0.001	0.000	0.925
R^2				0.510
		Climate with Built Environment and Demographics		
Constant	-7.695	2.654	0.004	
Precipitation	-0.001	0.000	0.115	0.962
Number of Units	0.002	0.000	0.000	0.394
Number of Stories	0.315	0.034	0.000	0.962
Year Built	0.011	0.001	0.000	0.920
Final Value	0.000	0.000	0.773	0.391
R^2				0.510

Table 8 Water demand models for commercial buildings

Variable	B	St. Error	Sig	Tolerance
		Climate		
Constant	59.74	4.569	0.000	
Temperature	-0.027	0.003	0.000	0.781
Precipitation	-0.001	0.000	0.000	0.781
R^2				0.038
		Climate with Built Environment		
Constant	-75.069	45.039	0.102	
Temperature	0.048	0.026	0.071	0.597
Precipitation	0.003	0.002	0.176	0.719

Table 8 continued

Variable	B	St. Error	Sig	Tolerance
Climate with Built Environment				
Acres	1.316	0.321	0.000	0.736
Number of Lots	0.025	0.014	0.090	0.918
Turf Fraction	1.146	1.298	0.382	0.776
Tree Fraction	0.793	1.672	0.637	0.869
R^2				0.369
Climate with Built Environment and Demographics				
Constant	-56.914	42.076	0.183	
Temperature	0.036	0.024	0.143	0.582
Precipitation	0.004	0.002	0.063	0.704
Acres	0.459	0.409	0.267	0.388
Number of Lots	0.035	0.014	0.015	0.869
Turf Fraction	1.897	1.226	0.128	0.745
Tree Fraction	1.025	1.548	0.511	0.867
Final Value	0.000	0.000	0.004	0.497
R^2				0.369

CHAPTER 4

NEIGHBORHOOD EFFECTS ON PARCEL-LEVEL WATER USE

In many cities in the U.S., water use exhibits distinct spatial patterns clusters of neighborhoods that have high or low overall water use (Chang et al., 2010; Guhathakurta & Gober, 2007; House-Peters et al., 2011). This clustering suggests that neighborhood characteristics may influence the water use of buildings and households within them. In general, it is expected that neighborhoods have certain characteristics that make them distinct from surrounding areas; they are internally similar. For example, a neighborhood is likely to have buildings of similar ages, residents of similar demographic groupings, and shared social values. To what extent is water use a characteristic of a neighborhood, versus being driven by the characteristics of individual properties?

This chapter attempts to identify the characteristics of neighborhoods that affected parcel-level water use. I hypothesized that neighborhoods should affect parcel-level water use via two mechanisms. First, there may be social norms that are shared at the neighborhood level which influence water use. An example would be landscaping preferences for turf grass. Second, there are structural characteristics of neighborhoods, such as the age of water infrastructure, that affect the efficiency of water use (Woodbury & Dollery, 2004). Other neighborhood characteristics may have effects as well, but there is very little previous research measuring the influence of neighborhoods on parcel-level water use.

In order to explore if there are neighborhood effects on parcel-level water use, I conducted a three-step methodology: 1) I assembled parcel-level data on a range of attributes (Chapter 3), 2) I measured neighborhood-level characteristics along nine dimensions that were derived using principle component analysis, 3) I estimated multi-level models to investigate the effects of both parcel and neighborhood characteristics on parcel-level water use. The water use data were from 74,575 parcels in 248 neighborhoods in Salt Lake City, Utah. I used census block groups as the boundaries of neighborhoods. Multilevel models partitioned the variance in water use between parcels and neighborhoods by including explanatory variables at each level. This is the first study to use this statistical method to examine the relationship between neighborhood characteristics and parcel-level water use. Further, this study is unique because of the large detailed databases for both neighborhoods and households. I sought to answer the following questions:

1. Are there neighborhood effects on parcel-level water use?
2. If so, which neighborhood factors affect parcel-level water use?

Literature review

Urban water use exhibits distinct spatial patterns across cities (Figure 8). Popular media has picked up on this phenomenon, and has publicly identified neighborhoods of high water consumption in times of regional conservation (Boxall, 2014; Sonderling & Grover, 2014). In the academic literature, spatial clustering of high and low water use has been observed and explained in terms of zoning (Shandas & Parandvash, 2010), socio-economic status (House-Peters & Chang, 2011), type of urban development (House-Peters et al., 2010), and the density and age of neighborhoods (Chang et al., 2010). These patterns of high and low water use suggest the existence of a neighborhood effect on water use.

The influence of neighborhoods on parcel-level water use can be explained by the "neighborhood effect," i.e., neighborhoods influence the behaviors and composition of residents within them. However, a neighborhood effect has rarely been explored in the water use literature, and previous theory development in this context is sparse. I must therefore examine literature from parallel fields such as urban planning, epidemiology, and sociology to define the neighborhood effect.

The neighborhood effect

That neighborhoods are distinct geographies has been established in the fields of urban design and planning for over a century (Park, 1915; Perry, 1929; Sampson, 2012). Early efforts to define neighborhoods stated that neighborhoods were "natural areas" which were subsections of larger communities, nested within each other forming successively larger communities (Sampson et al., 2002). Neighborhoods have been defined by social interactions (Hester, 1975) and by physical characteristics (Sampson, 2012). The geographic extent of neighborhoods varies depending on the research questions (Garner & Raudenbush, 1991); however, for this study, it is important to note that nearly all research on the effects of neighborhoods relies on neighborhood boundaries at the census block group or tract level as defined by the U.S. Census Bureau

(Sampson et al., 2002).

The best evidence supporting the existence of neighborhood effects is from a social experiment conducted by the U.S. government in the 1990s. In 1994, the U.S. Department of Housing and Urban Development implemented the Moving to Opportunity for Fair Housing Demonstration (MTO) in five U.S. cities (Leventhal & Brooks-Gunn, 2003). The program gave participants (low-income U.S. families) different types of vouchers for housing. A third of participants were given vouchers to housing in neighborhoods in any part of the city they chose, one-third received vouchers to housing only in census tracts with a poverty rate of 10%, and finally a control group received no new assistance. This experimental research design allowed for the isolation of the neighborhood effect.

In the MTO experiment, the neighborhood effect was observed to significantly affect the mental health of adults (Kling et al., 2007), where parents who moved to low-poverty neighborhoods reported lower levels of distress than parents who remained in impoverished neighborhoods (Leventhal & Brooks-Gunn, 2003). Participants who moved into neighborhoods with low poverty rates had lower obesity prevalence as well (Ludwig et al., 2011). Not all possible life outcomes demonstrated significant relationships to the neighborhood effect, but other investigations from around the world have yielded significant relationships between neighborhood characteristics and quality of life outcomes (Dawkins et al., 2005; Galster et al., 2008).

Neighborhood effects are generally thought to reflect both social and physical processes. Social effects reflect the influence of institutions, neighborhood norms, and social networks through which information is passed. Physical processes capture the impacts of configurations of the built environment, including different types of buildings, infrastructure, and land development patterns. This chapter is built on a conceptual model that relates both social and physical processes of neighborhood effects on parcel-level water use (Figure 9).

Social processes of neighborhoods

Neighborhoods are where shared activities and experiences occur, resulting in social groups and common values and loyalties (Hester, 1975; Galster et al., 2008; Mayer, 1997). As such, neighborhoods can influence the behavior, attitudes, and values of the residents within them. For examples, the social conditions of neighborhoods affect employment (Galster et al., 2008), educational attainment (Mayer, 1997), racial segregation (Dawkins et al., 2005), school readiness and achievement, behavioral and emotional problems, and well-being (Leventhal & Brooks-Gunn, 2000). The social dynamics of residents in neighborhoods also influence water use (Corral-Verdugo et al., 2002; Larsen & Harlan, 2006; Ouyang et al., 2014). Neighborhood norms can create social pressure to maintain certain types of landscaping to conform to a neighborhood's image, protect property values, or to keep the neighbors happy. The strength to which the social norms or attitudes are shared varies widely, and can shape water use behaviors if they are related to outdoor irrigation of landscapes.

Information about water conservation and behaviors may be communicated from neighbor to neighbor either directly through social networks, or by observations of the outdoor landscaping and irrigation of neighbors. When social networks in neighborhoods are strong, communication between neighbors is highest. For example, the effectiveness of implementing water conservation measures in a drought-prone Australian community was based on the strength of connections between neighbors (Miller & Buys, 2008). This study demonstrated that in neighborhoods where residents knew each other well, conservation messages were communicated effectively among neighbors and that the neighbors acted together to reduce water use.

An example of indirect communication and observing water conservation efforts between neighbors comes from Mexico, where Corral-Verdugo et al. (2002) found that when people observed their neighbors conserving water, it increased their motivation to conserve water. On the other hand, if people thought their neighbors were wasting water, they were more likely to use more water. Some social norms are formally institutionalized at the neighborhood scale, for example, homeowner associations. Neighborhoods with homeowner associations generally use more water because of mandatory lawn maintenance policies (Harlan et al., 2009).

Water use behaviors and norms that develop early in life can also be resistant to change. In a 2008 review of conceptual models of urban water use, Randolph and Troy (2008) found that cultural path dependencies, or long-term trends, shape an individual's water use behavior, making it hard for them to be able to change their water use. The long-term trend in many U.S. neighborhoods has been a preference for single family detached residential properties with irrigated lawns. Tian et al. (2014) found that 60 years of housing preference for detached single-family residential parcels persists, and these parcels are generally associated with well irrigated lawns.

Physical structure of neighborhoods

The physical structure of neighborhoods can influence the behavior of residents within them. For example, transportation planners have identified links between the physical characteristics of the built environment (measured at neighborhood scales) and travel behavior (Cervero & Duncan 2003). Physical characteristics of neighborhoods such as density, diversity, and design have consistently been found to influence travel behaviors of residents within neighborhoods (Ewing & Cervero, 2010; Tian et al., 2014). In other words, these physical characteristics directly facilitated certain behaviors. These findings do not directly relate to water use, but demonstrate that physical characteristics of neighborhoods influence behavior.

The physical structure of a neighborhood probably influences parcel-level water use. For example, the age of a neighborhood is correlated to the age of the water infrastructure, both in the houses and between the houses. Inefficient appliances or leaky pipes would be a characteristic of most buildings in older neighborhoods built before federal water efficiency rules were implemented in the early 1990s. Evidence of how neighborhood age affects water use is mixed. On the one hand, in Hillsboro, Oregon, newer neighborhoods consumed almost twice as much water during droughts in summer months (House-Peters & Chang, 2011). In Phoenix, Arizona, older neighborhoods with older infrastructure were found to use more water (Guhathakurta & Gober, 2007).

The physical structure of a neighborhood may also interact with social processes by shaping the development of social norms and the formation of social connections described above (Garner & Raudenbush, 1991). For example, the physical template for outdoor landscaping created when a neighborhood is built reflects the norms of the time period, but once built, can define the 'status quo' that social norms often seek to protect. Similarly, the physical design of a neighborhood may facilitate or constrain interactions among residents of the neighborhood (Garner & Raudenbush, 1991).

The complementary effect of self-selection

Residents choose to live in neighborhoods, effectively grouping themselves together on common characteristics (Sampson, 2012). This occurrence has been called self-selection. Self-selection is well studied in the urban planning and transportation fields. The discussion in the transportation field is that individuals, who prefer to live in neighborhoods that are walkable, self-select by moving into those neighborhoods (Cao et al., 2006). In this sense, some of the effects attributed to neighborhoods may instead reflect the characteristics of families and individuals that are attracted to that type of location (Sampson, 2012). Arguing for self-selection, researchers would state that the effects attributed to neighborhoods is instead caused by the attitudes of families and individuals that have chosen to live there. However, I still observe that neighborhood characteristics influence the residents within, whether by altering behaviors or by influencing the composition of residents who choose to live in the neighborhood. Robert Sampson (2012) concurred with this point by suggesting that rather than dismissing the role of individual selection effects, we recognize that self-selection is itself a neighborhood effect.

Self-selection introduces methodological challenges when trying to separate the neighborhood effects from the effects of individual or family attitudes, which may or may not be causally associated with neighborhood characteristics (Plotnick & Hoffman, 1999). When analyzing neighborhood effects, it is important to choose a statistical method that ensures that effects attributed to a higher level are not simply a consequence of cumulative choices of individuals within the lower level (Hauser, 1970). Multilevel modeling is one such statistical technique (Garner & Raudenbush, 1991).

Shortcomings to previous neighborhood analysis

There is room for improvement on research of water use at the neighborhood level. First, several studies restricted their analysis to single family residential units (Chang et al., 2010; Wentz & Gober, 2007), which ignored the substantial contributions of semiattached residential, commercial, industrial, and multifamily uses to total urban water use (Morales et al., 2011). Second, the data collected at the neighborhood level can be greatly expanded. For example, some studies relied solely on U.S. Census Bureau statistics (Chang et al., 2010), despite the availability of other sources related to potential drivers of urban water use at the neighborhood level. This research includes variables never before analyzed in this respect.

The research that has explicitly measured the effects of neighborhoods on parcel-level water use can also be improved. One effort relied on a small sample of houses, used self-reported measures of land-cover, utilized crude measures of urban structure, and only measured a few variables at the neighborhood level (Ouyang et al., 2014). Another mixed building-level attributes with neighborhood-level measures of demographics and land use zoning (Shandas & Parandvash, 2010). By not accounting for the nested structure of the data, it was difficult to know how much variation in water use was attributable to individual characteristics vs. neighborhood characteristics.

This chapter helps to fill these gaps by analyzing neighborhood effects on households utilizing detailed databases, and employing multilevel models to account for the nested structures contained in the analysis of neighborhood effects.

Methods

Measures of climate, demographics, and the built environment were collected at the parcel level for Salt Lake City, Utah, in 2011. The details were described in Chapter 3. The following section describes the data sources for neighborhood level characteristics.

Neighborhood-level measures and data sources

I chose to use the census block group (CBG) as the boundary of a neighborhood. Within the Salt Lake City Public Utility service provision boundary, there were 248 CBGs. CBGs contained between 600 and 4,000 people (U.S. Census, 2013). Other research on water use at the neighborhood level has also used CBGs as the unit of analysis (Chang et al., 2010; House-Peters et al., 2010; Ouyang et al., 2014). To characterize neighborhoods, I used 47 indicators at the neighborhood level that capture characteristics that have been linked to water use outcomes: land cover, land use, biophysical context, built environment, housing and household characteristics, population demographics, and information on municipal public water systems. A complete list of variables, data sources, and justifications are found in Jackson-Smith, Stoker, and Buchert (2014). To reduce the complexity of the analysis, the 47 variables were condensed into a set of uncorrelated latent variables using principal components factor analysis to capture underlying features that distinguish commonalities and differences between neighborhoods (Ritters et al., 1995; Sampson et al., 1997).

The factor scores used here were created for a larger project using data for all 1,384 CBGs in a 10-county region in northern Utah that had adjusted population densities over 100 persons per square mile (Jackson-Smith, Stoker, & Buchert, 2014). A principal components factor analysis with orthogonal rotation identified nine factors that explained 76.4% of the variation. These factors, and the key variables that were correlated with high scores on each factor, are described below.

- *FACTOR 1: Suburban (17.9 % variance explained).* The suburban factor described CBGs that have characteristics of classic suburban residential neighborhoods: a high percentage of single family homes, low levels of housing diversity, few renters, larger houses, and more people per household. This factor also captured places with relatively low residential population density, higher household income, and low poverty rates.
- *FACTOR 2: Microclimate (10.4%).* High scores on the microclimate factor described CBGs with higher elevations, cooler temperatures, and greater precipitation. The factor also captured places that have significant volumes of vacant housing and greater tree cover.
- *FACTOR 3: Nonresidential (10.0%).* High scores on this factor reflected CBGs with a high diversity of land uses and a low percent of land in residential uses. These places also tended to have lower population and housing density, less tree cover, and significant areas of nonirrigated agriculture/farmsteads or commercial or industrial land use.

- *FACTOR 4: Socioeconomic Status (9.0%).* High scores on the Socioeconomic Status (SES) factor described CBGs that had a relatively high percentage of adults with a BS degree or higher, high median housing value, high per capita income, and a high percentage of households with an income greater than $100,000.
- *FACTOR 5: Low-Density Development (8.9%).* High scores on this factor described CBGs that had large parcel and block sizes. These CBGs also tended to be places that were less likely to be served by a public water supplier. A map of this factor suggested that it captured areas on the exurban fringes of the study area.
- *FACTOR 6: Population-Housing Age (7.1%).* High factor scores described CBGs that have a relatively young population, large household sizes, and a high percentage of housing built since 1990, as well as a high (recent) median year built. One interesting finding is that age of population and age of housing stock are positively correlated in Utah—younger populations tended to live in more recently built housing (and vice versa).
- *FACTOR 7: Irrigated Agriculture/Greenness (5.6%).* This factor described CBGs that tended to be 'green' (e.g., have a high relative normalized difference vegetation index (NDVI)). This factor was associated with a high percentage of land in irrigated agriculture and farmsteads, high NDVI reflectance values (or significant areas of growing vegetation), and/or low percentages of impervious surface or commercial and industrial land uses.
- *FACTOR 8: Urban Parks and Open Space (4.3%).* High scores on this factor described neighborhoods that had a high percentage of land in urban open space

and parks.

- *FACTOR 9: Mobile Homes (3.4%).* The mobile homes factor described CBGs that had a high percentage of housing units that were mobile homes, relatively recently built housing stock, fewer 4-way intersections, and shorter median block lengths.

Statistical analysis

In order to characterize neighborhoods, I performed a principal component analysis with orthogonal rotation on the 47 neighborhood variables. Principal component analysis reduces a large set of correlated variables into a set of uncorrelated factors. The goal of this analysis was to identify latent variables that may not have been directly measured, or cannot be directly measured that capture differences between CBGs. This technique has been used in similar studies to identify differences and commonalities between neighborhoods (Ritters et al., 1995; Sampson et al., 1997).

I used multilevel modelling (MLM) to analyze the effects of neighborhood factors on parcel-level water use. I used MLM because of the nested structure of the data: parcels are nested within neighborhoods. Parcels within neighborhoods share the same neighborhood context, which implies that they are not independent. MLM accounts for nested data by relaxing assumptions of randomness and independence (Garner & Raudenbush, 1991). Furthermore, MLM models partition variance between neighborhoods and parcels, where variance in parcel water use will be explained partly by neighborhood characteristics, and partly by parcel characteristics (Doyle et al., 2006). The partition of variance at different levels improves estimation of coefficients and quantifies the effect of the neighborhoods on individual parcel water use (Larsen & Merlo, 2005). Multilevel modelling also is an improvement over spatial regression in that the method identifies specific characteristics of neighborhoods that influence water use, rather than simply identifying if there is a spatial pattern to water use.

I removed all parcel-level cases with incomplete records (n=608), and estimated three sets of models: one including all parcels, one limited to residential parcels (single family, duplex, triplex, fourplex, apartments), and one for commercial water users (businesses, hotels/motels, and restaurants). Models were estimated to explain variation in both total annual water use and estimated outdoor use for residential parcels and commercial parcels. Average outdoor use was calculated based on the difference between water use in the winter months, assumed to be all indoor, and water use in the summer months averaged over the summer months (May-October). Both dependent variables were non-normally distributed, so I use the natural log of both variables. All calculations were computed in HLM 7, Hierarchical Linear and Nonlinear Modeling software (Raudenbush et al., 2010). The nine factors identified by the principal component analysis were the neighborhood level variables. Simultaneously, the models controlled for key predictors of water use at the parcel scale.

Each model was initially developed as a null model, which contained no predictor variables at either scale. Null models were useful for two reasons. First, they allowed the calculation of the intraclass correlation coefficient (ICC). The ICC value indicates the proportion of variance in the outcome variable (i.e., water use) that could be explained by neighborhood level factors. Second, null models established a baseline for model fit. Because there is not an equivalent statistic to R-squared in MLM, I can only compare the fit of specified models based on relative improvements in what is known as the deviance statistic. Lower deviance represents better model fit. After estimating the null models, I then added predictor variables at both levels. Model fit improved as a result, and the statistical significance of this improvement was determined using the chi-square statistic, where the degrees of freedom were designated as the difference in the number of parameters estimated. I also included random effects on several parameters. When estimating models for commercial uses, I did not include any random effects as they did not prove to be statistically significant.

Results

I organized the multilevel model results by user type: all users, residential parcels, and commercial parcels.

The random effects of the two level multilevel model for all types of users (residential, commercial, industrial, parks and municipals, miscellaneous) are presented in Table 9. The first significant finding was the value of the ICC of 0.24. This finding indicated that 24% of the variance in parcel level water use was attributable to variations at the neighborhood scale. In other words, up to 24% of the variation in observed water use at the parcel level could be explained by neighborhood characteristics.

The fully specified model fit compared to the ANOVA model showed that there was a significant improvement in model fit: the chi-square statistic =3,361.59, and p<0.001. Further, the fully specified models presented here resulted in the lowest deviance statistic. This calculation yielded a pseudo r^2 of 0.4889. I estimated cross-level random effects (indicated in Table 9 by an asterisk) on four level 1 variables because I anticipated high variance around the group mean within neighborhoods. These choices were confirmed as all random effects were statistically significantly different than zero.

The MLM model results indicated that all modelled characteristics of parcels were statistically significantly associated with annual water use. Larger properties, more kitchens, and more bathrooms were all statistically significantly associated with higher annual water use. The year that the property was built was statistically significantly associated with water use, but the effect size (both the coefficient and more importantly the t-ratio) was very small. This model suggests that newer parcels were associated with higher water use. Parcels that were more expensive also tended to use more water.

The land cover of the property was also statistically significantly associated with annual water use, where a higher fraction of the property that was covered with vegetation the higher the annual water use. Property ownership was associated with a reduction in water use.

Neighborhood-level findings

Several neighborhood factors were statistically significantly associated with annual parcel level water use. The neighborhood factor that demonstrated the strongest effect on parcel level annual water use, as measured by both the coefficient and the t-ratio, was the suburban factor. Higher suburban factor scores were associated with greater annual water use. Neighborhoods with high suburban factor scores contained a high percentage of housing units that were detached single family homes, a low percentage of renter occupied units, low land use diversity, a high percentage of large family households, and had low poverty rates (Table 9).

Also significant, but with smaller effect sizes, were the nonresidential factor, the population-housing age factor, the irrigated agriculture factor, and the mobile homes factor. The population-housing age factor indicated that younger neighborhoods, both in age of residents and the age of properties, were associated with higher parcel level annual water use. Each of these factors are associated with an increase in annual water use. Several factors were found to have no statistically significant association with parcel level water use: socio-economic status, low-density development, and urban parks and open space factors all had no statistically significant effect on annual water use (Table 9).

Residential parcels

Because the drivers of water use decisions for commercial and residential properties likely differ, and in order to provide greater resolution to the results, I estimated separate multilevel models only using residential parcels. In Salt Lake City, a majority of annual use occurs in the summer months for outdoor irrigation. Therefore, I modelled both annual water use and average outdoor use. I estimated two random effects models for residential parcels, one for annual water use, and the other for average outdoor (Table 10). For residential properties, the value of the ICC was again 0.24. The model fit and model structure are presented in Table 10. The models included variables estimated using a random effect (indicated in Table 10 by an asterisk), and all random effects were statistically significantly different than zero.

Parcel-level findings

The residential parcel-level findings for both annual and average outdoor use were similar to the model for all user types. The one difference was that for annual water use, the housing tenure of the residential parcel was not significant, and for average outdoor use, properties that were owned were associated with higher outdoor water use. This was contrary to the model containing all parcels. For outdoor water use, the effect of lot size and vegetation fraction was greater than annual water use. Conversely, the effect of bathrooms and kitchens was lower for average outdoor water use.

Neighborhood-level findings

The residential models revealed that neighborhood factors affected annual and outdoor water use differently. For example, higher socioeconomic status factor scores were associated with higher use only for average outdoor water use. Another difference was that the population-housing age factor was significant for annual water use, but not for outdoor water use. The urban parks and open space factor was significant for outdoor water use, but not for the annual water use model.

There were also differences among the residential models and the model for all parcels. The coefficient for the socioeconomic status factor was not significant in the model for all users, but was significant and positive for residential annual water use, which suggests that areas with wealthier and better educated populations use more outdoor water (net the effects of other variables in the model). The population-housing age factor and the urban parks and open space factor were not significant in the model for all users, but were significant for residential properties. The population-housing age factor was statistically significantly associated with higher water use for annual residential water use (but not for outdoor), and the urban parks and open space factor was statistically significantly associated with a reduction in average outdoor water use for residential properties.

Because the suburbanity factor was again the most significant factor influencing water use, I examined the effects of the individual variables that constitute the suburbanity factor on annual water use. The following table indicates the significant variables, their coefficients, and the t-ratio. Average parcel size, the percentage of rental housing units, the average household size, and the population density were not significant. The effects of density are apparent; higher residential density and higher density of single-family residential parcels is associated with reductions in parcel level water use.

Commercial parcels

I also investigated neighborhood effects on commercial water use. Again, I estimated a two level multilevel model. The models, fit and structure for commercial parcels are presented in Table 11. The ICC for commercial properties was lower than the models for residential and all users (0.12), which suggests that neighborhood characteristics have less impact on variation in parcel level water use for commercial parcels.

Parcel-scale findings

The parcel-scale findings were mostly similar to the residential models and all user models. Data availability for commercial properties altered our selection of parcel scale variables, i.e., the tax assessor data does not include the tenure of commercial properties. The major difference was that the lot size of commercial properties was not statistically significantly associated with either annual water use or average outdoor water use. Also, the direction of effect for number of bathrooms was contrary to the other models.

Neighborhood-scale findings

The commercial models revealed a key difference between commercial properties and residential properties, as well as all users. The suburban factor was not statistically significantly associated with either annual water use or average outdoor water use. Also, the socioeconomic status factor was statistically significantly associated with both annual water use and outdoor water use. Two factors were significant for the average outdoor water use models but not for annual water use: the nonresidential factor and the irrigated agriculture factor.

Discussion and implications

This paper investigated whether neighborhood characteristics influence parcel-level water use in the Salt Lake City area. Using data at the neighborhood and parcel levels, I estimated multilevel models to explain variation in indoor, outdoor, and total annual parcel water use. The hypothesis that there was a neighborhood effect on parcel-level water use is substantially supported. The strongest evidence came from the ICC measures.

The ICC measures revealed that up to 24% the variation in parcel-level water use could be explained at the neighborhood scale. If there were no neighborhood effects, I would not expect to have found such a high ICC. To find that that 24% of the variation in water use can be explained by neighborhood characteristics is quantitative evidence of a neighborhood effect on parcel level water use. Interestingly, the ICC is much lower when considering only commercial properties (ICC=0.12). I see this as evidence that there are neighborhood effects, and that they influence residential properties more so than commercial properties. Assuming that people in residential properties communicate with neighbors more so than people who own commercial properties, at least about water use and landscaping, the difference in ICC between residential and commercial properties makes sense as it supports our social aspect of the theoretical framework. All of the social mechanisms were hypothesized to apply to residential land uses but not necessarily commercial.

Several neighborhood factors were significantly associated with water use, but the effects differed based on whether the parcels were residential or commercial uses, and whether water use was disaggregated to reflect outdoor use. The neighborhood factor with the greatest effect on residential and all users water use was the suburban factor. Neighborhoods with high suburban factor scores were characterized by primarily residential single-family detached buildings, homogenous and owner-occupied housing stock, family households, and relatively low poverty rates. These neighborhoods were highly homogenous both in social and structural characteristics. It is possible that living in a suburban area might expose residents to social norms that reinforce higher water use (especially outdoor use), since these areas tend to have more uniform landscaping patterns and dominant social norms. As such, the results indicate that a homogeneity of buildings and social context leads to a homogeneity of high water use.

Previous research in parallel fields indicates that residents in homogenous neighborhoods exhibit homogenous behaviors: voting preferences were similar in homogenous suburbs (Oliver & Ha, 2007), social ties were stronger (Gans, 1961), and information exchange was higher (Shemesh & Zapatero, 2014). If there were attitudes towards water use that existed at the neighborhood scale, such as landscaping preferences, they would be more strongly shared in homogenous neighborhoods. I suspect this is true, but unfortunately, this study was not able to capture attitudes of residents and the degree to which norms are shared between neighbors because I was limited to available secondary data sources. Future research should further this investigation into neighborhood norms.

When I modelled outdoor water use separately from total annual use, I found several interesting differences in which neighborhood factors affected parcel level water use. For example, the population-housing age factor was significant for annual use, but not for outdoor use. This factor captured the physical age of the properties in the neighborhood, likely a correlate of the age of water infrastructure between and in the houses. I think that the age of the appliances and fixtures in the house would influence indoor water use more so than outdoor water use, an assumption supported by the models (Table 9). A second example was the socio-economic factor which was significant for residential outdoor water use, but not for total annual use. This factor measured the wealth of a neighborhood. I think that wealthier neighborhoods would put a greater emphasis on the outward appearance of properties, and that this neighborhood norm would result in higher water use for irrigating properties. If this is the case, it is reflected in the residential multilevel models (Table 9).

When analyzing all water users, three neighborhood factors that I expected to have an influence on parcel level water use were not statistically significantly associated with higher parcel level water use: socioeconomic status, low-density development, and urban open space. I was surprised because each of these factors describe average parcel-level characteristics, which have previously been found to affect urban water use. Specifically, income (Ferrara, 2008) and lot size (Abrams et al., 2012) have been linked to higher water use. However, the model results indicate that at the neighborhood-scale, these factors were not statistically significantly associated with parcel level water use. This indicated that these were drivers that operated at the parcel scale, and not at the neighborhood scale. This finding stands in direct contrast to previous research on neighborhood water use that found that socio-economic status and lot size were associated with higher water use (Chang et al., 2010; House-Peters et al., 2011).

Nonetheless, both the social and structural theories of why neighborhoods would affect parcel level water use were supported by the multilevel models. Structural attributes of neighborhoods such as the population-housing age factor were statistically significantly associated with total annual use for both residential properties and all users combined. Social conditions, such as the suburban factor and socio-economic factor, were both associated with higher levels of outdoor water use for residential properties. Additional resolution into these theories could be provided by future research that measures and assesses neighborhood norms, and the degree to which they are shared in and between neighborhoods.

I found substantial empirical evidence that there were neighborhood effects on parcel level water use in Salt Lake City, UT. This research was not the first to investigate the effects of neighborhoods on parcel level water use (Ouyang et al., 2014), but this chapter improves on previous efforts by using multilevel modelling and richly detailed data at both the neighborhood and household scale. Further research is needed to expand the external validity of this research because the specific findings were based on a single case study. This chapter suggests that future research efforts should identify and explore community norms related to water use. The findings suggest that both structural characteristics and social conditions of neighborhoods affect parcel level water use. I was unable to identify what those norms were, and the degree to which they vary from neighborhood to neighborhood. This work should represent a building block for future research on the neighborhood effects on water use.

This chapter and the previous chapter established that the built environment is a determinant of urban water use. Chapter 3 found that lot size, number of bathrooms/kitchens, and land cover were the strongest predictors of urban water use in Salt Lake City. Chapter 4 identified neighborhood characteristics related to the built environment, including development patterns and housing type. Evidence from other U.S. cities also supports the findings that the land use decisions affect urban water use. Clearly, the way in which we build cities affects how water is used. The next chapter of this dissertation seeks to demonstrate how these findings are relevant to the practice of planning, and urban water supply planning. Traditionally, it has been the role and responsibility of engineers to manage water supply in urban areas. The next chapter explores how urban planners can contribute to water conservation in urban areas.

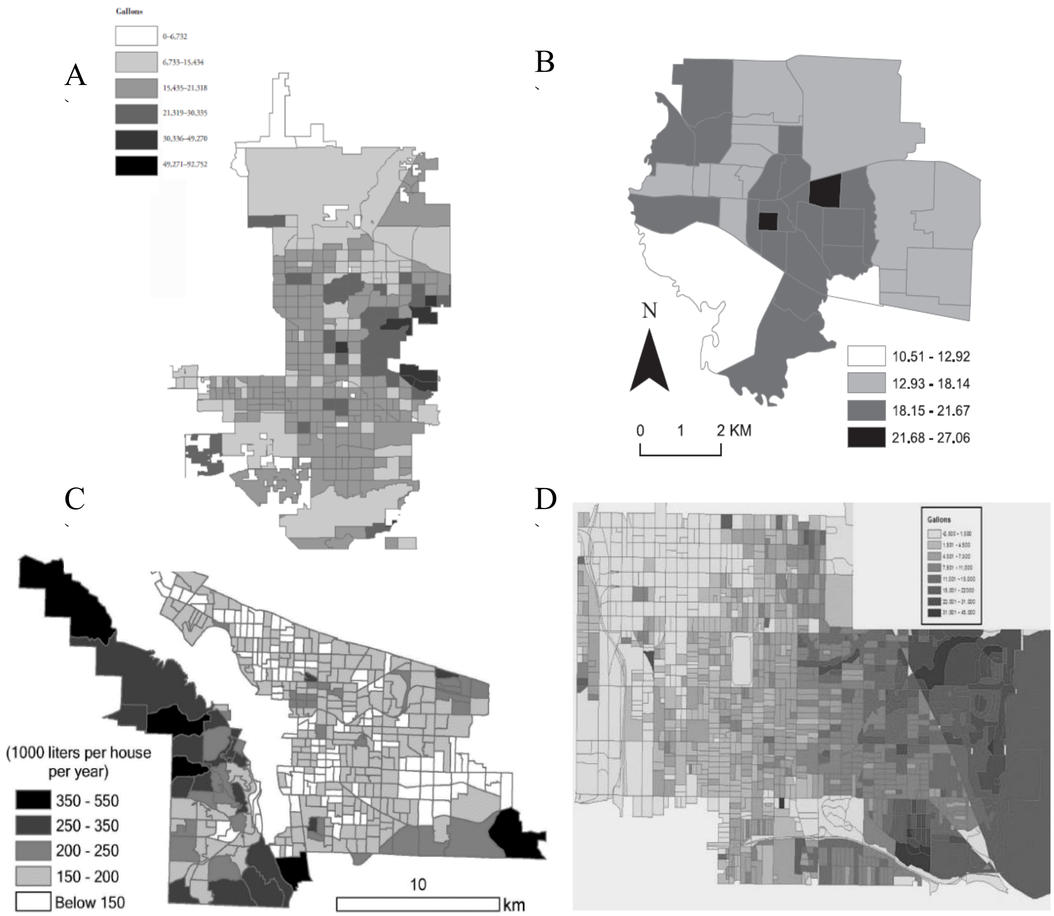

Figure 8 Spatial variation in water use across cities at the neighborhood scale. Adapted from A) Guhathakurta and Gober, 2007 Phoenix, AZ; B) Chang et al., 2010 Hillsboro, OR; C) House-Peters et al., 2010 Portland, OR; and D) Rothfeder et al., *In Review*, Salt Lake City, UT. Darker shades indicate higher water use.

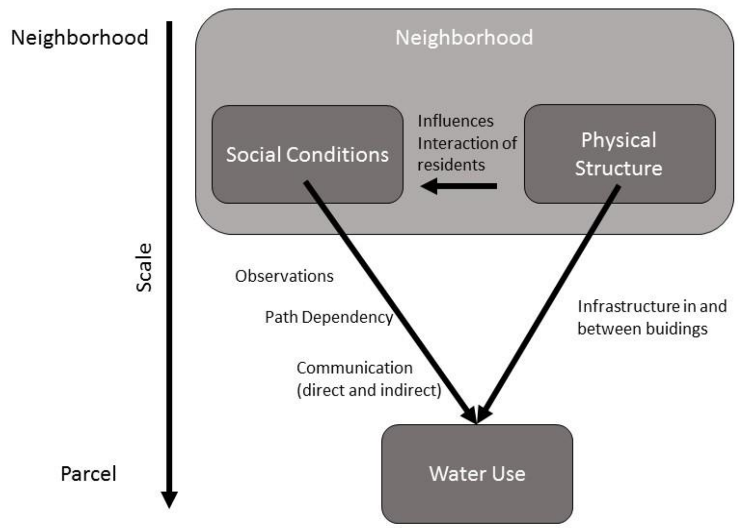

Figure 9 Conceptual framework relating neighborhood effects to parcel-level water use

Table 9 Random effects two level multilevel model

Variable	**B**	**S.E**	***T***	***P***
Level 1: Parcel Scale				
Total Acres*	0.896	0.088	10.945	0.000
Owner Occupied*	-0.027	0.01	-2.095	0.037
Number of Kitchens	0.216	0.012	16.739	0.000
Total Bathrooms	0.077	0.004	19.283	0.000
Year Built	0.001	0.002	6.674	0.000
Vegetation Fraction*	0.304	0.028	10.594	0.000
Final Assessed Value*	0.149	0.009	16.487	0.000
Level 2: Neighborhood Scale				
Intercept	7.714	0.451	16.986	0.000
Suburban	0.101	0.010	9.6	0.000
Microclimate	-0.015	0.014	-1.042	0.299
Nonresidential	0.06	0.016	3.635	0.001
SES	-0.011	0.009	-1.27	0.206
Low-Density Development	0.027	0.04	0.671	0.503
Population-Housing Age	0.038	0.013	2.785	0.006
Irrigated Agriculture	0.048	0.018	2.665	0.009
Urban Parks and Open Spa	-0.012	0.007	-1.585	0.144
Mobile Homes	0.03	0.01	2.843	0.005

***** Random effects were significant at $p<0.001$

Notes: Chi square =3,361.59 $p<0.001$, Pseudo $R^2 = 0.4889$

Model structure:

Level 1: *Level-1 Model*

Y = B0 + B1*(TOTAL_AC) + B2*(OWNER_OC) + B3*(NUM_KITC) + B4*(TOTALBAT) + B5*(YEAR_BUI) + B6*(VEGFRAC) + B7*(FINALVAL) + R

Level-2 Model

B0 = G00 + G01*(FACT_SUB) + G02*(FACT_ELE) + G03*(FACT_NON) + G04*(FACT_SES) + G05*(FACT_LGL) + G06*(FACT_POP) + G07*(FACT_IRR) + G08*(FACT_URB) + G09*(FACT_MOB) + U0

B1 = G10 + U1, B2 = G20 + U2, B3 = G30, B4 = G40, B5 = G50, B6 = G60 + U6, B7= G70 + U7

Table 10 Random effects two level multilevel model for residential properties

Variable	**Annual Water Use** B	*t*	*p*	**Outdoor Water Use** B	*t*	*p*
Level 1: Parcel Level						
Total Acres*	0.893	10.314	0.000	1.552	10.798	0.000
Owner Occupied*	0.02	1.886	0.060	0.144	8.872	0.000
Number of Kitchens	0.216	16.928	0.000	0.034	2.277	0.023
Total Bathrooms	0.077	19.246	0.000	0.042	7.626	0.000
Year Built	0.001	6.951	0.000	0.003	12.263	0.000
Vegetation Fraction*	0.305	10.511	0.000	0.601	12.515	0.000
Final Value*	0.146	16.538	0.000	0.213	17.387	0.000
Level 2: Neighborhood Level						
Intercept	7.612	16.907	0.000	1.597	3.126	0.002
Suburban	0.101	9.367	0.000	0.180	10.271	0.000
Microclimate	-0.01	-1.014	0.312	-0.01	-0.802	0.424
Nonresidential	0.057	3.309	0.001	0.108	3.603	0.001
Socio-economic status	-0.01	-1.206	0.230	0.059	3.575	0.001
Low-density development	0.025	0.634	0.526	0.015	0.289	0.773
Population-Housing Age	0.035	2.524	0.013	0.037	1.518	0.130
Irrigated Agriculture	0.047	2.607	0.010	0.155	4.952	0.000
Urban Parks/Open Space	-0.01	-1.394	0.165	-0.03	-2.130	0.034
Mobile Homes	0.028	2.618	0.010	0.043	2.419	0.017

***** Random effects were significant at $p<0.001$

Notes: *Annual Use*; Chi square =3,179.49 $p<0.001$, Pseudo $R^2 = 0.311$. *Outdoor Use;* Chi square= 112.089 $p<0.001$, Pseudo $R^2 = 0.195$

Model structure:

Level-1 Model

Y = B0 + B1*(TOTAL_AC) + B2*(OWNER_OC) + B3*(NUM_KITC) + B4*(TOTALBAT) + B5*(YEAR_BUI) + B6*(VEGFRAC) + B7*(FINALVAL) + R

Level-2 Model

B0 = G00 + G01*(FACT_SUB) + G02*(FACT_ELE) + G03*(FACT_NON) + G04*(FACT_SES) + G05*(FACT_LGL) + G06*(FACT_POP) + G07*(FACT_IRR) + G08*(FACT_URB) + G09*(FACT_MOB) + U0

B1 = G10 + U1, B2 = G20 + U2, B3 = G30, B4 = G40, B5 = G50, B6 = G60 + U6, B7 = G70 + U7

Table 11 Significant variables that constitute the suburbanity factor

Variable	**Coefficient**	***T*-ratio**
Natural log of residential density	-0.136	-1.95
Density of Single Family Residential Parcels	-0.421	-3.918
Median number of rooms	0.065	0.005
Percentage of family households	0.700	2.585
Poverty Rate	-0.248	-2.231

Table 12 Fixed effects two level multilevel model for commercial properties

Variable	Annual Water Use B	*t*	*p*	Outdoor Water Use B	*t*	*p*
Level 1: Parcel Level						
Total Acres	-0.003	-0.789	0.430	0.002	0.416	0.677
Meter size	0.808	28.584	0.000	0.768	22.141	0.000
Number of Units	0.344	9.826	0.000	0.271	6.365	0.000
Total Bathrooms	-0.133	-2.175	0.030	-0.24	-3.356	0.001
Vegetation Fraction	0.554	3.311	0.001	1.575	7.522	0.000
Final Assessed Value	0.002	5.062	0.000	0.002	4.147	0.000
Level 2: Neighborhood Level						
Intercept	11.083	96.970	0.000	8.281	58.893	0.000
Suburban	0.015	0.343	0.732	0.069	1.252	0.212
Microclimate	0.118	1.569	0.118	0.058	0.653	0.514
Nonresidential	0.066	0.922	0.358	0.234	2.640	0.009
Socio-economic status	0.109	2.382	0.018	0.195	3.482	0.001
Low-density development	-0.011	-0.080	0.937	0.301	1.721	0.086
Population-Housing Age	0.089	1.473	0.142	0.121	1.648	0.101
Irrigated Agriculture	0.087	1.159	0.248	0.211	2.301	0.022
Urban Parks /Open Space	0.026	0.669	0.504	0.009	0.199	0.842
Mobile Homes	0.098	2.246	0.026	0.175	3.289	0.002

Notes: *Annual Use*; Chi square =205.75 p<0.001, Pseudo R^2 = 0.268. *Outdoor Use;* Chi square= 33.119 p<0.001, Pseudo R^2 = 0.221

Model structure:

Level-1 Model

Y = B0 + B1*(MTRSIZE) + B2*(NUMBEROF) + B3*(TOTAL_AC) + B4*(TOTALBAT) + B5*(VEGFRAC) + B6*(FINALVAL) + R

Level-2 Model

B0 = G00 + G01*(FACT_SUB) + G02*(FACT_ELE) + G03*(FACT_NON) + G04*(FACT_SES) + G05*(FACT_LGL) + G06*(FACT_POP) + G07*(FACT_IRR) + G08*(FACT_URB) + G09*(FACT_MOB) + U0

CHAPTER 5

THE PLANNER'S ROLE IN URBAN WATER CONSERVATION

Droughts and increasing populations are forcing hundreds of cities in the U.S. (mostly in California) to implement water conservation strategies in order to reduce urban water use (Association of California Water Agencies, 2015). The effectiveness of these efforts varies greatly and sometimes does not produce the desired results. For example, in one city in Texas, the drought restrictions imposed on residential water use have incentivized the wealthiest residents to drill private wells to access the unregulated groundwater beneath their homes (Root & Satija, 2013). While an extreme example, many other cities have had trouble implementing effective water conservation programs. In some cities, “water police” are required to patrol and ticket excess water users in order to enforce water restrictions (Huff, 2014). In California, news reports indicate that the state governor’s emergency declaration asking residents to voluntarily cut their water use by 20% was unsuccessful and many residents responded by increasing their water use (Weiser & Reese, 2014). Now, mandatory restrictions have been implemented. Each example should be a clear indication that managing demand and achieving water conservation is not an easy or straightforward task, and that strategies must be crafted and implemented carefully.

The specific focus of this chapter is how urban planners can help manage demand and promote urban water conservation. Planners have a unique role to play in urban water conservation because of their authority to influence land use decisions. However, urban planners are generally uninvolved in water demand management and water conservation efforts despite calls to integrate land use and water supply planning. Integrating land use and water supply planning expands the suite of tools available to better achieve water conservation, but integration only occurs occasionally. In this chapter I describe the examples of planners working with water managers to promote urban water conservation. I also describe the more commons situation, where there is no communication between land use planners and water managers. The content of this chapter is based on interviews with water managers and land use planners from five U.S. western states. The goal of this work is to highlight good examples and practices of planners working towards water conservation so that land use and water supply planning can integrate in order to improve the effectiveness of water conservation across the U.S. I sought to answer the following research questions:

1. In what ways are planners currently involved in urban water demand management and conservation?
2. Are there specific strategies that planners can implement to help conserve water?
3. What are the impediments to planning interventions, and how can they be overcome?

The disconnect between land use planning and water conservation

In the U.S., water quality and availability are among the best in the world. In order to achieve these gains in water quality and availability, water management was made efficient and effective. Water supply planning is the responsibility of water engineers, who are tasked with supporting future land development and population growth (Gober et al., 2013). Water supply planning is subordinate to land use planning because water managers must accommodate the demands of population growth without questioning how much growth occurs and what type of growth occurs (Gober et al., 2013). The current management system has been described as a "centralized and siloed system" replete with a "complex structure of regulations" (Mukheibir et al., 2014).

This traditional approach to urban water management has divided the roles and responsibilities of managing water and land use land use planning. This division has been described as a "governance gap" between land use planning and water planning (Bates, 2011). The governance gap is caused because water planning occurs at the state or regional level, while land use planning is conducted at municipal or local scales; staffing or funding are limited; and an institutional culture of risk aversion and a lack of innovation exist (Gober et al., 2013). The division is clear when land use planners assume that water will not be a limiting factor for growth and economic development (Bates, 2011). When water *is* a limiting factor, the traditional approach of water managers has been to build new infrastructure, augment supply, and acquire new water rights (Larson et al., 2013). Each of these solutions does not require the integration of land use and water supply planning.

In California, consistent droughts have spurred the creation of state laws SB 221 and SB 610, which require land developers to prove a 20-year water supply as a condition to build large new developments (over 500 units) (California Department of Water Resources, 2003). In periods of drought, these laws led to the denial of multiple new building permits, as well as modifications to development plans and the provision of high-efficiency appliances (Steinhauer, 2008). Both laws were created due to the necessity of coordinating local water supply and land use decisions. It is important to note, however, that California had to enact these laws after 100 years of separate land use and water supply planning. Land use planning and water supply planning are integrated only in Arizona. The 1980 Arizona Groundwater Management Act stipulates that new developments must demonstrate a 100-year assured water supply. This law has made land use planners more aware of the impacts of new developments on water supply (Gober et al. 2013).

These state laws contrast with the common realities of local land development permitting, where the criteria for new developments seldom include the consideration of long-term water supply. For example, in Utah and Colorado, concerns over water scarcity have spurred water agencies to promote statewide educational campaigns to reduce water use. Water conservation is seen by water managers to be critical to meet future demand, yet land use planners in these states continue to permit additional development and growth without requiring a long-term water supply to be assured. We see advanced planning efforts linking land use and water supply in California and Arizona because these states have already had to confront the realities of water resource degradation and depletion. Where once planners would never consider limiting population growth because of uncertain water supplies, in a “future haunted by scarcity, the unthinkable may be thinkable after all" (Reisner, 1993, p. 14).

The link between land use planning and water conservation

Water supply and land use are connected. As land is converted from a natural condition to agricultural or urban uses, water is needed to support the conversion. In urban environments, land use is related to water supply because additional development requires additional water. Certain land developments require more water than other forms of development. For example, suburban housing with lawns can increase regional water consumption substantially (Domene & Sauri, 2006; Hill & Polsky, 2007). Land development also affects water supply and quality through the conversion of pervious to impervious surfaces (Baker, 2003). In highly impervious watersheds, water quality and supplies deteriorate due to pollution runoff from impervious surfaces. When water supplies become scarce, the relationship between land use and water supply is even clearer: urban development is either restricted or supported by the availability of water (Woltjer et al., 2007).

When specifically examining how the built environment affects water consumption, there is a wealth of research from which to establish the link between land use and water supplies. At the household scale, the age of a building, the size of the lot, the amount of turf, and the type of building all affect household level water use (Guhathakurta & Gober, 2007; Polebitski & Palmer, 2010; Rockaway et al., 2011; Stoker & Rothfeder, 2014). At the neighborhood scale, characteristics such as average household size, the percent of homes with swimming pools, and average lot size all affect water use (Chang et al., 2010; Guhathakurta & Gober, 2007; House-Peters et al., 2010; Wentz &

Gober, 2007). At the city scale, the cumulative impacts of the lower scales contribute to total water use. For example, municipal water use in Europe is about 50% of that in the U.S. due to the fact that the lots on which houses are built are much smaller and more people live in apartments compared to U.S. (Novotny, 2010). Since there is a link between the built environment and water use, urban planning clearly has a role to play in influencing water use and water supply.

Integrating land use planning and water conservation has fallen under several labels: Integrated Water Resource Management (Mitchell, 2005), Sustainable Urban Water Management (Brown & Farrely, 2009), or "One Water" (Mukheibir et al., 2014). The common themes among these new paradigms are that they are adaptive, participatory and *integrated*. The change that is needed is philosophical and socio-institutional more than technological (Brown & Farrely, 2009). The integration of land use and water management should have advantages over our current management strategies. The integration expands the suite of management tools to promote urban water conservation. For example, land use planners can implement landscaping ordinances, or require conservation design standards on new developments. These are actions that water managers have no authority to implement. For the new paradigm to be fully realized, urban planners must engage in water conservation efforts.

In order to show how urban planners can influence water demand, and in turn preserve water supplies, I employ a conceptual framework developed to describe urban water systems and the relationships between structure, actors, and water (Hale et al., 2015). I simplified the framework to address the relationships between land use planning, water management, and water supply (Figure 10). In the framework, water supply is primarily influenced by water use, and water demand is influenced by both the structure of the built environment (as described above) and an individual's water use behaviors. Figure 10 indicates the influence that water managers and land use planners exert on the system by arrows. Land use planners influence the structure of the built environment through permitting, zoning, and landscaping ordinances. Together with water agencies, land use planners can influence water use behaviors through educational campaigns, demonstration gardens, and other strategies. Water managers directly influence supply through supply augmentation, and indirectly by modifying the water use behaviors of individual water users, i.e., water conservation programs. I argue that planners have an important role to play in urban water conservation because they have the authority to influence the structure of the built environment, while water managers do not. Together with water managers, the suite of conservation tools can be greatly expanded.

While calls for integrating land use planning and water management have been frequent and the potential for land use planners to influence water use is clear, widespread integration has yet to happen (Bates, 2011; Gober et al., 2013; Shandas & Parandvash, 2010). Furthermore, there has been no research that has asked practicing water managers and land use planners how they currently integrate responsibilities to promote urban water conservation. I attempt to fill this gap in knowledge by conducting interviews with a range of experts in water management and land use planning to identify how land use planners and water managers can better integrate the management of water supply. I also sought to clearly identify the planner's role in urban water conservation.

Methods

I conducted interviews to investigate the planner's role in urban water conservation. Collecting qualitative data is appropriate because it can capture otherwise hard-to-measure details about collaborations, conflicts, obstacles, and outcomes.

Interviews were conducted from August 2014-April 2015. In total, I interviewed 17 individuals for this research. Study participants included water utility managers, state and regional water managers, water conservation managers, urban planners, and water resource researchers. Participants were from five Western U.S. states, Arizona, Colorado, California, Nevada, and Utah. I selected the initial participants based on their job title and organizational affiliation. Job titles that included water conservation, or water resource management, or land use planning were selected first. Then, using a snowball selection approach, I asked additional individuals to participate based on the recommendations of their colleagues. The interviews ranged from 30 to 60 minutes in duration, with most interviews lasting 60 minutes. The interviews were semistructured, and included the following standard questions:

1. Is water conservation important?
2. How do land use planners impact water conservation?
3. How do you plan for future urban growth?
4. What conservation efforts are being implemented already?
5. What data and information are being used?
6. Are there any barriers or disincentives to water conservation?
7. What is the level of collaboration between water managers and planners?
8. Whom else should I speak with?

Follow up questions were frequent, and were based upon the participants responses to the initial questions. Oftentimes, only one question was required for several minutes of response. I kept thorough notes during the interviews. After the interview, I wrote the notes into coherent passages summarizing the interview. These interview summaries were then sent back to the participant to ensure accuracy. At this stage, the participants were encouraged to add new content, and suggest revisions or omissions to improve the quality of the data. Most participants made revisions and clarifications on the interview summaries. To encourage thoughtful and open responses, the research design assured anonymity in the analysis and dissemination of the interview results. Therefore, interview quotations and content presented below are anonymous and do not reveal the information on the participants beyond generalizable descriptions of job duties and roles. Only the author, who conducted the interviews, read the interview summaries for confidentiality purposes.

Findings

The following sections contain the results of the interviews organized by subject. The subjects include current conservation efforts, disincentives for conservation, planning for urban growth, collaboration between water management agencies and land use planners, the role of developers, and the role of planners. To ensure the confidentiality of participants, I use the following terminology to identify organizations, roles and responsibilities, rather than using specific job titles or names.

Regional planner: An individual employed as a planner at a regional or state level.

City planner: An individual employed as a planner at the municipal level.

Water manager: An individual at the management level of a state or regional water agency.

Water utility: An organization that sells water directly to customers.

Water agency: An organization that manages water. The agency may or may not sell water to customers, may or may not be a wholesale provider, and is responsible for water supply planning and development.

Current collaborative conservation efforts

Across the Western U.S., a range of conservation strategies have been implemented to manage water demand and promote urban water conservation. Most strategies are designed and implemented by water managers and water utilities; however, there are examples of collaborative conservation efforts between land use planners and water managers. These examples are discussed in the section on collaboration between land use planners and water managers. This section reviews conservation efforts that are currently being pursued by water management agencies.

The current conservation strategies include educational campaigns and workshops, rebates for water efficient appliances, demonstration of "water-wise" gardens, and land use ordinances. All of the interviewed water managers used educational campaigns. Educational campaigns attempt to achieve conservation by effecting a long-term ethical change in the way people use water. One interviewee drew the parallel to successful educational campaigns in the U.S. to discourage littering. Instead of littering, the educational messages link individual water use behaviors to regional water supplies.

Another conservation strategy involves demonstration water efficient landscaping. Water agencies and utilities build and operate aesthetically pleasing "water-wise" gardens to provide examples of what the alternative to turf grass would look like (Figure 11). In several states, state and regional water management agencies assist in the funding of these demonstration gardens. These gardens are open to the public and are intended to show that water efficient landscapes can be visually appealing. The goal is to reduce the negative perceptions that residents may hold about xeriscaping and reduce residential preference for turf grass lawns.

Tiered water rate structures are another conservation measured employed by water managers and utilities. These pricing structures charge higher rates for greater use. To effectively reduce water use, tiered water rates must be set to send price signals to customers. One regional water manager reported that the tiers the agency set are too wide, which allows a customer to use a lot of water before triggering a higher rate. The upper tiers also do not go high enough to create strong financial incentives to reduce use.

Water budgets are increasingly used as a conservation strategy. Water budgets prescribe an estimated amount of water that an owner should use and is sent by the public utility to the customers. In one city, water budgets were very successful at reducing water use; however, in another city, this strategy was not effective. In the unsuccessful case, the water budgets were set too generously so as not to offend customers. The interviewee reported it was possible that the budgets were set too high and inadvertently encouraged the residents to use more water.

Conserving indoor water compared to outdoor water use deserves special consideration. All the interviewees reported that outdoor water conservation is the chief priority. Water used for outdoor irrigation is much higher than indoor use, and is generally thought of as less necessary than indoor uses, i.e., bathing, washing, and cooking. In one region, all water that is used indoors is purified, and then returned to the region's water supply in a reservoir. In this case, there is no need to conserve indoor water use as is recycled as an additional source of water supply. However, indoor water use can be conserved by improving the efficiency of indoor appliances, and should constitute a portion of a suite of conservation actions.

The important theme emerged from the interviews is that no one single conservation action should be exclusively pursued, but rather it is necessary to employ a combination of conservation strategies. An example of this combined approach comes from one large western city, where drought conditions forced a water utility to implement water use restrictions. These restrictions limited water use to two days per week. However, the restriction was modified if customers adopted a water budget to use only 12 gallons per square foot of property per week. This strategy was very effective in saving water, especially for commercial customers. At the same time, the public utility pursued several other conservation strategies, including rebates and information on water efficient appliances (plumbing fixtures; toilets, faucet aerators, urinals, appliances, and washing machines). Finally, the public utility increased the price per unit of water by 1-6% each year to account for the cost of service. This example is intended to demonstrate that multiple conservation actions taken together are effective at managing demand and reducing water use in a period of drought.

Collaboration between water management agencies and planners

All the water managers I interviewed indicated that they frequently collaborate with other water managers. For example, there are regional conservation organizations that consist of member water agencies. Membership in these organizations benefits the individual water agencies by achieving economies of scale with conservation efforts. Program costs are reduced, messaging is consistent, and experiences can be shared among member agencies. Typical collaborative efforts of these regional organizations are fairs, educational campaigns, and rebate offers on water efficient appliances and fixtures. When a partnership is more encompassing, the conservation groups will include landscapers and sometimes developers. Regional conservation organizations have been successful in developing and implementing development codes that homebuilders followed in order to promote water conservation.

A generality can be made about the level of collaborations between land use planners and water managers: "the level of collaboration depends on the necessity of conservation." The closest collaborations are in states and regions that are facing the greatest scarcity. Where scarcity is less pressing, the level of collaboration between land use planners and water managers is only just beginning to happen, or is not happening at all. Smaller cities have less collaboration between land use planners and water managers/utilities.

In a small city, one water manager described the level of collaboration between planners and water providers as "zero communication." When asked if additional collaboration would be beneficial, the interviewee responded that it would be nice to collaborate with the land use planners, but no effort has been made so far. Several interviewees reported that water managers were at the whim of planners' decisions on where, how much, and what type of development occurs. For example, a development was planned at 18 units per acre. The water managers in this city have found that this development density is more water efficient than low-density development. However, the original developers were unable to complete the project, and a new developer took over the plans. The new developer proposed a density of 11 units per acre, and the city council approved the plans regardless of the water use implications. Here is where an important linkage should occur.

Land use planners and water managers/utilities should together evaluate the feasibility of new developments from a water supply perspective. Or, if one development is inconsequential on system-wide water supply, the collaboration should determine what will be the cumulative impacts of growth on water supply in a city. Almost everyone interviewed shared this perspective and saw a need for collaborating with land use planners. I interviewed several water managers who indicated working with land use planners on a project or two, but still expressed a desire for more collaboration.

The first step towards collaboration is communication and network building between water managers and land use planners. The second type of collaboration reported by interviewees is long-term regional planning. These planning meetings are broadly inclusive, involving municipalities, federal and state organizations, non-governmental agencies, water managers, and land use planners. The goals of the planning processes are to protect water resources, plan for urban development, and make regional land use decisions. The organizers of these processes are sometimes regional planners. In at least one major planning initiative, the goal was to recognize the link between land use and water supply/quality. One participant interviewed described the process as "exciting, but slow."

The third reported type of collaboration between land use planners and water managers is developing and implementing land use regulations. A good example of collaborating on landscaping ordinances is from a large western city where land use planners worked with the public utility to change building codes to improve water efficiency. The public utility expressed its desire to promote water efficient developments and took the lead on prescribing the design standards. The city planners responded and incorporated changes to municipal landscaping codes. At the same time, both the public utilities and city planners brought in stakeholders to investigate landscaping code changes and identify if there could be a broader range of acceptable planting choices for landscapes.

Once the land use regulations are developed and implemented, water managers and land use planners need to collaborate on enforcement. One interviewee highlighted that state-wide implementation of landscaping ordinances has been ineffective at reducing water use. They suggested it was likely because city planners failed to enforce regulations, or failed to properly review the plans. This example highlights the need to have a water expert in a land use planning office.

Planning for urban growth

As mentioned before, population growth is currently stressing water supplies and will likely be more of a stressor in the future. Planning for adequate water supplies and urban growth is best accomplished through a close collaboration of land use planners and water managers. The interviews revealed that about a third of the water managers collaborate with regional planners to plan for future urban growth. All of water managers reported that they receive estimates of population growth from regional planners and must develop long-term water supply plans (as required by state laws).

In the collaborative planning process, regional planners collaborate with regional water managers to produce a range of population estimates for the future growth. Together, they examine how different types of development would affect water supplies. Many stakeholders are involved and explore the implications of different growth and climate scenarios. In some scenarios, there are water supply gaps and in others conservation efforts are sufficient to support future growth.

More commonly, there is no collaboration between land use planners and water managers when planning for future population growth use this estimate to develop long-term water supply plans. In contrast to the collaborative planning process, scenarios of growth are not utilized. The single population estimate is less robust to future uncertainty than a range of scenarios. Furthermore, not all water users are accounted for in an estimate. For example, one small city that hosts year round tourism, and therefore has an effective population greater than the resident population.

Collaboration between water managers and land use planners seems to produce more robust long-term water supply planning. The major benefit is that land use planners must consider the effects of growth on water supplies, instead of assuming it will be there. By considering water supply, land use planners can adapt the form of development, or the location of development to minimize stress on water supplies. Water managers benefit from the collaboration because they can work with land use planners to develop growth scenarios that are robust to changing future conditions.

Disincentives and barriers to water conservation

Some interviewees reported reasons to not conserve water. Recognizing these barriers and disincentives is important for water managers and land use planners so that future conservation efforts are successful. The principal disincentive to conservation is that conservation reduces revenues. In most utilities, revenues are directly linked to water sales. Minimizing water sales, i.e., conservation, would therefore reduce a water supplier's revenue. Property taxes and federal funding often supplement a public utility's revenue from water sales, but in general, these sources are not as significant as water sales. As a result, water utilities are nervous about dropping revenues if conservation is widely adopted.

This concern is amplified in wet years, when precipitation reduces demand for outdoor irrigation and further conservation efforts will cut into revenues. One water management agency expressed that if conservation curtails use to a point where rates have to increase to pay for infrastructure costs, users will respond that "we did what you wanted" by working toward conservation, and yet are rewarded with higher rates.

The second disincentive to conserving water is demand hardening. Demand hardening is when water conservation eliminates or reduces "excess" water use, leaving only a critical "base" level of water use. Beyond this point, further conservation gains are more difficult because there is no "excess" water left to conserve. Residents may be willing to not wash their cars on the front lawn, but further conservation gains may require more drastic and unpopular actions. As such, one interviewee indicated that letting customers use as much as they want now in nondrought years is a good thing.

There is concern that if water conservation is aggressively pursued, it will cast an image of the city that is antigrowth, or unable to accommodate population and business growth. In addition to the aversion to discouraging growth, many water managers interviewed expressed a desire not to anger the public. One water manager felt like mandates restricting growth or regulations on landscaping seemed like “big brother” and government overreach. For example, when asked whether or not landscape regulations should be implemented, one water manager expressed that there is no desire to go into people’s backyards and tell them what to do. Homeowners associations may be potential barriers to water conservation as well because they can require landscaping practices that are water intensive. Research in arid regions has found that homeowners associations are associated with higher water use, supporting this possibility (Guhathakurta & Gober, 2007).

The role of developers and landscapers

The most important conservation goal is to reduce residential outdoor irrigation. Developers and landscapers have unique roles to play in this regard because they build the amount of irrigable landscaping on a property, as well as determine the composition of vegetation on the landscapes. In general, developers and landscapers are not involved in water conservation efforts, and some interviewees indicated that developers and landscapers can be resistant to conservation efforts. In one city where building codes were designed to reduce outdoor water use, the developers supported changes in building codes because the homes they build use less water use, countering public antigrowth sentiments.

This was the best example of water managers engaging developers and land use planners in water conservation efforts. The water management agency designed landscaping ordinances and development codes for residential and commercial properties in conjunction with land use jurisdictions. They were designed by committee as part of a regional conservation organization and public stakeholder outreach meetings with homebuilder's associations, commercial building managers, car wash industry, golf course industry, etc., to refine and critique the design standards. Developers were supportive of the proposed standards, because at the time, the region was experiencing rapid growth and drought. By supporting regulation, builders mitigated antigrowth sentiment and calls for building moratoriums.

The uniform standards were implemented in multiple jurisdictions including counties and municipalities and are the responsibility of member agencies to enforce and implement. For residential properties, there is no irrigated turf in the front yard, and no more than 50% of backyard can be turf, with a maximum of 5,000 square feet and a minimum allowance of 100 square feet. The ordinances, combined with market-driven reductions in lot sizes, resulted in new homes that used 40% less water. The landscaping ordinances are critical to achieve savings in consumptive water use, as most of the efficiency gains for indoor water use have already been made.

I asked another water manager of a small city if they collaborate with land developers and the interviewee responded that developers "might have a heart attack if they had to think about conservation." The anticipated concern of developers would be that conservation leads to more expensive developments, and that houses designed for conservation may unattractive to potential buyers. Other interviewees reported that developers have been resistant to engaging in conservation initiatives, again because the perception is that it will be too expensive, or will not be good for customers.

The key lessons are that developers should be involved early on in the process of developing land use regulations. If the developers are resistant to incorporating the design changes in order to facilitate water conservation, they can hamper implementation. If developers and homebuilders can adopt and support conservation design, there is good evidence that water savings will be achieved.

The role of planners

Planner's involvement in water conservation ranges from nonexistent, to multiple collaborative projects integrating land use planning and water management. The model for future water supply planning and land use planning is collaboration. Where no collaborations exist, work is needed to bridge agencies and organizations. The first step that is needed is to begin a dialogue. Relationships need to be built in order to develop an understanding of the needs and processes of what were previously separate planning agencies. From there, a range of possibilities is available. Several concrete actions that city and regional planner can implement revealed themselves during the course of the interviews.

The most important thing planners can do is to work water resources into their planning processes, and to consider water resources in land use decisions. This may involve staffing an individual from a water management agency within a land use planning organization. An individual with expertise in water management would help with the technical challenges that not all planners are trained for. If not directly staffing a water expert, planners should regularly involve their local water managers and incorporate these managers into planning processes and decisions. The goal is to break down planning silos and recognize water resources in land use planning processes and decisions.

The most frequent request of planners from water managers is to implement and enforce land use regulations to reduce water use. Planners are uniquely situated to implement landscaping ordinances, as the profession has the legislative authority to set and enforce design regulations in cities. The public utilities can regulate water rate structures and water pricing, and land use planners can implement regulations and landscaping requirements for new development and redevelopment. The water managers know how to conserve water, and their expertise should be utilized by planners when designing and implementing landscaping ordinances. Ordinances need to produce high-quality results aesthetically. Here is where planners, and especially urban designers can bring their unique skillset to the table. Unattractive examples of water efficient landscaping have deterred people from adopting. Urban planners can incorporate water-wise landscaping into attractive neighborhood and city designs.

Design standards on new developments would help achieve water conservation. For outdoor water use, the total outdoor area of the property, and how that area is used, are substantial determinants of water use. Design standards should reduce the outdoor area that needs to be irrigated, and changing what is planted, prioritizing certain grasses/plants/trees for water efficiency would all affect water use. Specific details of the regulations should be informed by the expertise of water managers and public utilities.

One water manager wanted land use planners to set density targets for new developments. The water manager and the water agency had found that traditional low-rise (2-3 story) apartment buildings were the most efficient buildings on a per-dwelling-unit basis. Low-rise apartments were even more efficient than high rise because the larger buildings implement cooling towers that increase their water footprint. The water manager wanted land use planners to set and implement city or neighborhood density targets for future development.

Planners can also help prevent demand hardening by formalizing agreements that water that was conserved would be saved, and not allocated towards new developments. Therefore, agreement is needed between planners and public utilities which state that any water conserved would be saved, not allocated toward new development. It is the concern of public utilities that water conserved will result in the permitting of new developments, undoing any conservation gains that have been made, and further solidifying the perverse incentive of public utilities to not conserve as much as they can in order to preserve a "buffer" of conservation possibilities.

As noted earlier in the section on projecting future urban growth, the sole population estimate provided by regional planners is inappropriate for water supply planning purposes. Municipal and regional planners should instead provide scenarios of population estimates, which provide a range of estimates. In order to be collaborative, the regional planners can coordinate their modeling of scenarios with the public utilities. Further, planners should attempt to project commercial, industrial, and tourism growth as well because each requires water supply to support and have not been accounted for in past population estimates. The uncertainty in estimating these figures is substantial, hence the importance of providing a range of scenarios to plan for. As time passes, water managers, coordinating with planners, can adapt and pursue supply augmentation or conservation programs as one scenario becomes more likely, and others become unlikely.

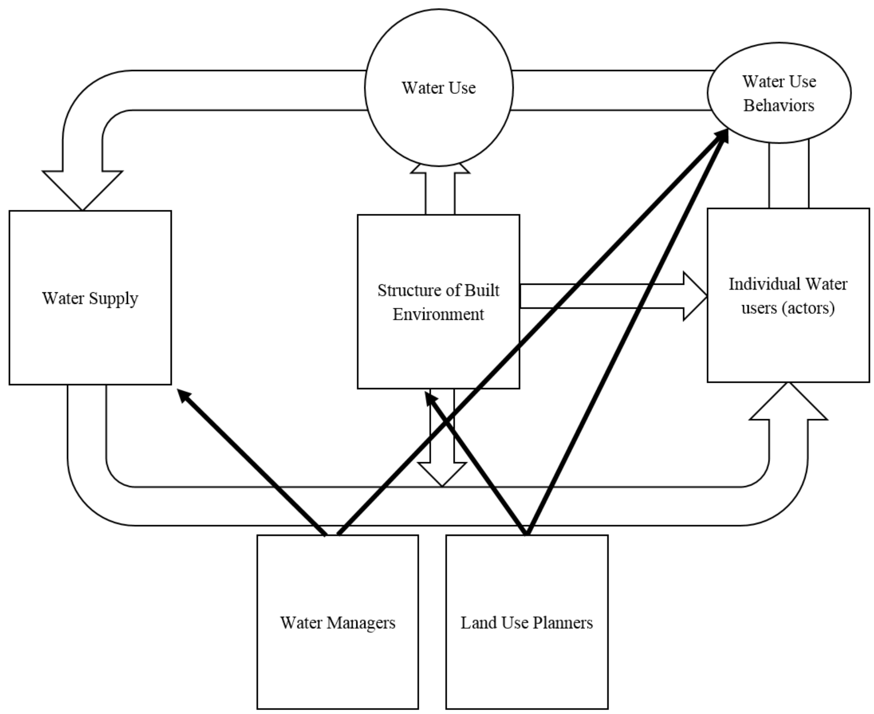

Figure 10 Conceptual framework linking planning, water management, and water supply. Adapted from Hale et al. 2015.

Figure 11 Water wise demonstration garden in Scottsdale, Arizona. Photo credit: Patrick Lewis

CHAPTER 6

CONCLUSIONS AND STRATEGIES

This dissertation shows that the way we build cities influences how we use water. I developed detailed databases on water use to empirically identify which characteristics of the built environment affect water use. From the available data, it was clear that there are certain features of the built environment that strongly influence water use: lot size, turf cover, age of buildings, number of kitchens and bathrooms, and the number of units among others (Tables 4-8). The land use and types of development in neighborhoods also influences water use. In order to complement the quantitative data, I conducted interviews with water managers and land use planners to identify how planners could support water conservation efforts. Before I present conclusions from this work, I acknowledge some limitations of this dissertation. These limitations suggest future avenues of research.

Limitations and future research

The role of land cover characteristics such as the fraction of the parcel that is covered by turf and trees warrants further research. For example, the models for single-family buildings (Table 3) indicated that a greater fraction of the parcel covered by trees was associated with higher water use, while the opposite was found for semiattached buildings (Table 5). Variation in tree species across the city may account for the conflicting results: some species of trees require more water than others, and people water accordingly. Or, tree cover may reduce overall water use on properties due to shading and cooling of lawns. Unfortunately the remotely sensed data cannot measure if there is turf grass underneath a tree canopy. It is possible that people are watering turf grass and not the trees themselves. The resolution and availability of data limits the conclusions this study can make on the effects of tree canopy on water use. Mounting evidence from research on Urban Heat Islands suggests there are tradeoffs to consider when planting trees for their cooling effects in cities, and further research is needed to determine whether tree canopy reduces or increases water use (Pataki et al., 2011).

Identifying neighborhood norms and the social factors that drive water use is the critical next step of this research. Much of residential water use remains unexplained in the models (Tables 3-5). I predict that the remaining variance would be explained by in part by information on the irrigation system of a property (automatic timers, drip irrigation etc.), and by the preferences, values, and attitudes of the person who turns on the tap. This dissertation demonstrated that the built environment is an influence on water use, but the effects of individual behaviors should be just as important. To more fully understand patterns of urban water use, it will be critical to explore the extent that preferences, attitudes, and values affect water use. Several studies have utilized questionnaires to assess how individual characteristics influence water use, but our understanding can be greatly expanded and interesting questions remain. My future research will utilize investigate how attitudes, preferences, and norms influence water use.

The quantitative chapters (Chapters 3 and 4) of this dissertation utilized cross-sectional research designs. The limitations inherent in cross-sectional research designs prohibit conclusions of causality between variables. I have found that lot size has a strong association with water use. I have not found that larger lot sizes cause higher water use. A randomized or quasi-experimental research design would improve the validity of this study. A true randomized experiment is likely impossible, but a quasi-experimental research design may be feasible. For example, I could test the influence of the built environment on water use using a quasi-experimental design and examine the change in water use when a household relocates to a different property. The control group would be households that remain in their properties from year to year. As the comparison group, I would select households that move to a new property. This move would be the experimental treatment, as the new property has new physical characteristics, but the household's characteristics (i.e., attitudes, norms, and preferences) would remain constant. The dependent variable would be water use. Conclusions could be made on whether the physical characteristics of properties determine water use, or whether individual characteristics determine water use.

In Chapter 5, I suggested that there are neighborhood norms that influence water use. The norms may have included landscaping preferences, desires to maintain outward appearances of properties, or long held conceptions that lawns are necessary. There was no available data to measure neighborhood norms, but this would be an interesting line of research. Survey research may help fill this gap in available data. If a survey were administered in several different neighborhoods, norms could be compared across neighborhoods. In addition, water use records could be compared between neighborhoods, and similarly to Chapter 5, the effects of neighborhood norms could be quantified.

Finally, the empirical research in this dissertation was conducted in only one city in the U.S., limiting the external validity of this research. Therefore, I cannot offer conclusive comparisons of findings to other research in different parts of the world. Comparisons are also complicated because of the different methodologies employed as well. Specifically, the multilevel model results in this context are novel, and comparisons cannot be made at this time. The methodologies I used are replicable, and the data for calculations and models may be available in other regions. Despite these limitations, several conclusions from this dissertation can be made:

<u>The built environment is a determinant of water use</u>

This dissertation demonstrated that certain features of the built environment influenced water use. The first piece of evidence comes from Chapter 3. In all the parcel level models (Tables 3-7), the model fit improved substantially when measures of the built environment were included. For example, the commercial water use model had a R^2 of 0.02 when only estimating the effects of climatic variables, and increased to 0.51 when built environment variables were added. This effect was observed for each of the urban land use types, and was a strong indication of the importance of the built environment on water use. The characteristic of the built environment that had the greatest effect on water use was the size of the parcel. In each of the urban land use types, the greater the size of the parcel, the larger the effect on water use. The other major drivers of urban water use in Salt Lake City were the number of bedrooms, kitchens, and bathrooms.

These findings were supported by the results from Chapter 4, which found that larger properties, more kitchens, and more bathrooms were all statistically significantly associated with higher annual water use, even while controlling for neighborhood characteristics. The models in Chapter 4 also identified some neighborhood characteristics related to the built environment that influence parcel level water use. The neighborhood factor with the greatest influence on parcel level water use described neighborhoods that had a high percentage of detached single family homes, a low percentage of renter occupied units, low land use diversity, and a high percentage of large family households. This is evidence that the composition of housing and development types in a neighborhood influences water use. That the built environment influences water use is the foundation for the following conclusions and recommendations.

Current development

One conclusion we can make from this research is that we are not building water efficient cities. There are several findings that support this conclusion. The data indicate that there are properties in Salt Lake City that there are several examples of properties that use a tremendous amount of water. In one year, a single family residential property used 4.6 million gallons of water, an industrial building used 596.4 million gallons, and a single business used 154 million gallons (Table 2). To illustrate the absurdity, these three properties used enough water to fill the Pyramid at Giza with water, and then some (100,965,546 cubic feet was used in the three buildings, and the volume of the pyramid is 86,453,791 cubic feet). While these are extreme examples of high water use, they illustrate that far more water is being used than is actually needed. If only the highest water users reduced their use, a tremendous amount of water would be available for all other users. The highest water users should be the very first target for water conservation strategies and water use restrictions.

The evidence also indicates that buildings and neighbors that are being built are less efficient than they used to be. Almost all the models indicated that newer properties and younger neighborhoods use more water (Tables 4, 5, 8). Rather than becoming more efficient with the construction of homes and neighborhoods, we are building less water efficient developments. This is in spite of the federal regulations mandating water efficient appliances in new developments. The preferred development pattern in the U.S. for single-family detached residential properties persists (Tian et al., 2014), and this pattern is associated with higher water use (Table 8). The way we are currently building cities is stressing our water supplies.

Water use implications of future development

Cities across the U.S. are expecting to grow substantially in the coming years. The question is what that growth will look like. Will some cities continue to expand and sprawl? Or will the strategy be to increase density and focus growth in centers of development? Increased development density is the preferred strategy of many regions because of the recognized benefits of density: improved transportation accessibility, reduced infrastructure costs, improved walkability, and so on. A potential co-benefit of building cities more densely may be improved water efficiency and overall lower water use. Several conclusions can be made from this dissertation on the water use implications of future development.

In the neighborhood level analysis, homogenous suburban development was associated with higher annual and outdoor water use (Table 8). A property will use more water in a homogenous suburban neighborhood compared to a similar property in a mixed use neighborhood. This could be because of shared community norms and landscaping preferences that require a lot of water. If future development perpetuates suburban landscapes, it can be expected that water use will increase to support suburban development patterns.

However, if development patterns are denser, then the housing stock and composition will change from a predominance of detached single family residential properties to higher density residential properties. From the analysis of parcel level water use in Chapter 3, the data indicated that duplexes, triplexes, fourplexes, and single family residences did not differ in mean annual water use. In other words, overall annual use is approximately the same regardless of whether there were multiple families in a property. Per capita use is then lower, indicating improved efficiency. This gain in efficiency is likely due to the fact that the semiattached residential properties share a yard, and outdoor irrigation is the same for regardless of how many people live in a property. The transition to more dense development with a greater proportion of semistructured residential properties will likely reduce per capita water use.

In Chapter 4, there were key variables associated with the suburbanity factor that indicated that as density increased, there is an associated decrease in water use. Specifically, the results contained in Table 9 indicate that higher residential density and higher density of single family residential parcels is associated with reductions in parcel level water use.

Further evidence on the effects of density came from the interviews in Chapter 5. One water manager indicated that the regional water agency had conducted an analysis of water use and neighborhood density. The interviewee reported that the data showed that traditional low-rise (2-3 story) apartment buildings were the most efficient buildings on a per-dwelling-unit basis. Low-rise apartments were even more efficient than high-rise because the larger buildings implement cooling towers that increase their water footprint. This water manager wanted land use planners could implement would be identifying and implementing city or neighborhood density targets for future development. I concur with this water manager, and think that density targets for development is an appropriate water conservation strategy. Finally, a parallel effort found that the zoning in Salt Lake City had a statistically significant influence on water use, where zoning for single family large lots was associated with an increase in water use, compared to zoning ordinances for small lot single family residential properties (Rothfeder & Stoker, *in review*). The evidence suggests that as density increases, water use will decrease.

A water wise city would therefore look denser. The properties would have smaller lots, and smaller areas that require irrigation. Where irrigation is required, the landscape would be a mix of lawn and plantings with low water requirements. Inside the homes, there would be efficient appliances. There would be landscaping ordinances to ensure that new developments were built to be as efficient as possible. In all likelihood, the quality of life enjoyed by residents would remain the same, as water would be available to meet basic needs, as well as to irrigate attractive, albeit different looking landscapes

The planner's role

Several mechanisms exist for planners to shape the built environment, and I suggest that planners have four concrete actions that can be taken sequentially to promote urban water conservation and integrate land use and water supply planning (Figure 12). This process of integration is based off of the examples of successful integration and the recommendations of practicing experts in Chapter 5. The first step is to begin a dialogue and formalize collaborative relationships between planners and water managers. The goal is to break down siloes. After the collaborative working relationship has been established, regional visioning and planning is an appropriate first step. One specific action would be to develop scenarios of growth with estimates of population growth that include tourism projections and commuting workers to account for all users of water. Water managers and land use planners can then explore what the water use implications of future growth scenarios will be.

Further efforts should include implementing landscaping ordinances to minimize outdoor irrigation. These ordinances should be developed in collaboration with water managers so that the water manager's expertise is utilized. For example, water managers in Las Vegas developed landscaping ordinances and development codes that specify that no turf be allowed on the front lawn, and no more than 50% of the backyard can be turf grass. The land use planners at the municipal and county level have implemented these ordinances. In order to ensure effective implementation, planning organizations should staff a water conservation expert to oversee implementation. The ordinances must be visually appealing and urban designers can contribute to ensure that the ordinances produce aesthetically pleasing results.

A promising planning tool that has yet to be implemented for water conservation is form-based zoning. Form-based zoning codes differ from traditional land use zoning codes. Traditional zoning codes specify which uses are permitted, i.e., commercial, industrial, or residential. Form-based zoning emphasizes the physical form of the development rather than use. For example, form-based zoning strictly regulates development according to building heights, sidewalks, setbacks, construction details, and the planting of trees, even in some cases down to the acceptable species that can be planted (Sitkowski & Ohm, 2006). These specifications in the code could be designed to reduce the amount of water used. For example, the strict regulations provided by form-based zoning could minimize lot size as well as the size of the lawns on new developments. Other specifications in the code could identify drought tolerant species of vegetation with low watering needs that would replace water intensive traditional species of turf grass. Land use regulations and building codes have been effective in guiding growth away from disaster prone areas (Burby, 1997); perhaps now land use regulations and building codes can guide future developments to promote water conservation.

This strategy improves and complements landscaping ordinances and development codes. First, form-based zoning codes can be implemented in areas of cities rather than city-wide. This would allow city planners and water managers the ability to target new developments that will have potentially higher water use. The results in Chapter 4 indicate that homogenous suburban neighborhoods would be perfect candidates for form based codes aimed at water conservation. Form based codes also can prescribe density targets for neighborhoods.

Integrating land use and water supply planning

There needs to be integration of land use planning and water supply planning, as suggested most of the water managers that I interviewed. The best parallel can be traced to land use and transportation planning. Where once land use planning and transportation planning were conducted separately, it is now illegal to ignore the transportation impacts of new developments. Federal laws such as the Clean Air Act Amendments of 1990 and the Intermodal Surface Transportation Efficiency act of 1991 prohibit this separation of transportation planning and land use plans (Waddell et al., 2007). Planning for land use requires planning for transportation because the two are linked. Land use and water supply are linked; therefore, they must be planned together. Federal laws that required planners to consider water use decisions would go a long ways to speed up the integration of land use planning and water supply planning.

This research certainly is not the first to make this call (Brown & Farrely, 2009; Glennon, 2010; Mitchell, 2005; Mukheibir et al., 2014). However, it is the first to reach out to practicing experts to gain insights into how this integration can occur. Currently, political barriers need to be overcome, and almost all of the changes needed are political or socio-institutional. Therefore, to the extent possible, this research is also a call to department heads, mayors, council members, governors and other political leaders to make water conservation a priority. The involvement of upper levels of political leadership will help speed up the changes that planners might seek to implement. For those that lack the courage to make this change, scarcity will eventually force their hand.

Planners have an important role to play in water conservation. When looking back at a lifelong career in planning, Klosterman (2013, p. 162) wrote "without planning, communities can only stumble blindly into a future they make no effort to shape." This quote is directly relevant as cities and regions begin to face water supply catastrophes that have roots in water management decisions made decades ago. In one interview, a water resource researcher reported that there is "no water crisis, we have a water management crisis." I think, and so do the experts that I interviewed, that land use planners can help alleviate this crisis and contribute to water sustainability in the future by integrating land use and water supply planning.

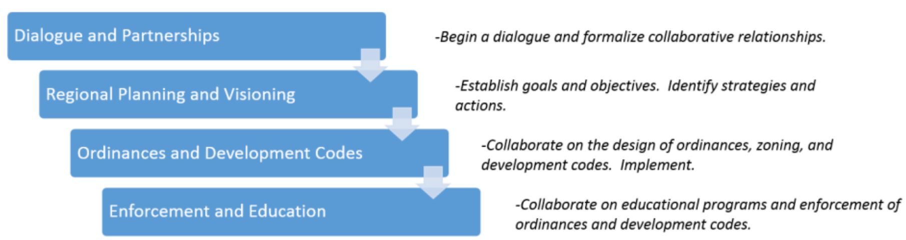

Figure 12 Suggested flow of integrating land use planning and water supply planning

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